THE GREENHOUSE EFFECT AND THE ALBERTA FOSSIL FUELS INDUSTRY

A Discussion Paper

E.J. Wiggins and W.J. Yurko

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SUMMARY

This study represents a preliminary attempt to assess the effects on the Alberta fossil fuels industry if international action is taken to limit emissions of "greenhouse gases," and the measures that might be considered to minimize any negative impact on the provincial economy. The study is largely qualitative and is intended only as a basis for further discussion or analysis.

Likely Global Actions

The suggested global actions to deal with greenhouse warming range from learning to live with climatic change to a drastic reduction in fossil fuel use. It is considered likely that some measures will be taken to minimize climatic change if there is international agreement that the threat is real, probably including the following:

- increased energy conservation
- a ban on the use of chlorofluorocarbons
- discouragement of land clearing
- replacement of heavier by lighter hydrocarbon fuels
- increased use of nuclear and renewable energy
- use of neat hydrogen as a transportation fuel

Implications for Alberta

One positive effect of such policies on Alberta should be an increase in demand for natural gas, both as a replacement for heavier fuels and as a source of hydrogen for upgrading these fuels. At the same time, a trend to reduced consumption of heavier fuels would probably result in smaller domestic and export markets for coal. Oil demand would probably decline over a period of time with increased conservation and replacement by other heating and transportation fuels. The suggested countermeasures are the development of methods of reducing CO_2 emissions from fossil fuels to permit their continued use. The development of renewable energy sources and of non-fuel markets for hydrocarbons could also serve as supplemental forms of economic activity for Alberta.

Reduction in CO_2 Emissions

The implementation of effective measures to reduce the net additions of CO_2 to the atmosphere from fossil fuel burning would serve as potent arguments for extending fossil fuel use. The approaches considered in the study are:

1. Increasing the H/C ratio of fuels to reduce the CO_2 emissions for a given energy output;

2. Reducing the amount of CO_2 emitted during production, processing, and transportation of the fuels;
3. Capturing the CO_2 released during combustion of the fuel for use or long term storage;
4. Removing CO_2 from the atmosphere with growing vegetation;
5. Increasing the efficiency of energy utilization;
6. Reduction of CO_2 emissions from sources other than fossil fuels.

The technology for converting heavy oil or coal to light liquid hydrocarbons or to substitute natural gas is largely available now, although it is not always economic at current energy prices. The accompanying increase in H/C ratio greatly reduces the amount of CO_2 released per unit of combustion energy and should permit continued use of these resources as well as making them more convenient to transport and use. The availability of hydrogen is the key to this solution, as recognized in the Alberta Hydrogen Program.

Considerable reductions in CO_2 emissions during production and processing of the fuel can be achieved by optimum choice of processes and energy sources, particularly in natural gas processing and in-situ bitumen production. Capture of the by-product CO_2 produced during steam-methane reforming or steam-oxygen gasification is an integral part of this approach.

Capture of CO_2 from combustion of fuels is much more difficult than from processes such as steam-methane reforming since the CO_2 in flue gas is diluted with large amounts of nitrogen from the combustion air. The current processes for recovering CO_2 from flue gas have high capital costs and require large amounts of low pressure steam for regeneration of the absorbent. While competitive with other routes for producing CO_2 as a desired product, they would impose a large cost penalty on a coal-fired power station as a disposal process. The total amount of CO_2 to be recovered is considerably in excess of the probable demand for enhanced oil recovery, and the remainder would have to be placed in long-term storage in depleted reservoirs. While this appears to be quite feasible, any new consumptive uses that could be developed for CO_2 would reduce the net cost of disposal. Combustion with oxygen in place of air would greatly facilitate the recovery of CO_2 from flue gas, but would involve major changes in boiler furnaces and power generation equipment.

The growth of vegetation removes CO_2 from the atmosphere by photosynthesis, so that an increase in total vegetation growth through reforestation or other measures would result in a net decrease in CO_2 additions to the atmosphere. The forest areas required to absorb CO_2 at the rates emitted from major sources such as thermal power stations are very large, but Alberta has large tracts of marginal land that might be diverted to this purpose. The accumulated growth of plant material must be eventually utilized in ways that do not quickly return CO_2 to the atmosphere.

A significant reduction in CO_2 emissions should be possible through further improvements in the efficiency of energy utilization in all of the major energy use sectors. While this reduction in emissions will be obtained at the direct expense of reduced fossil fuel consumption, it will often be the most cost-effective approach and is almost certain to form part of any over-all plan for CO_2 control.

A reduction in CO_2 emissions from sources other than fossil fuel combustion could serve as a trade-off against fuel emissions. The main industrial sources of CO_2 in Alberta apart from fossil fuel processing are nitrogen fertilizer, lime, and Portland cement manufacture. The natural sources of CO_2 such as decomposition of vegetation and soil organic material are extremely large, although the opportunities for reducing these emissions are probably limited to conversion of forest and agricultural wastes to biomass fuels. Improved forest fire control will also lead to some reduction in CO_2 emissions.

Many of the suggested measures require further research or literature study to determine the most effective methods of application and to reduce costs. A brief list of such research areas is included in the report.

Flexibility Important in Meeting CO_2 Reduction Targets

The indications from this preliminary study are that a mandated conversion to energy sources which emit less CO_2 to the atmosphere would benefit the natural gas industry, but would progressively reduce the markets for Alberta coal and conventional crude unless countermeasures were taken. There are a number of such possible measures, and a series of flow charts is appended to the study to indicate the options which would be available under various external constraints. While global action will obviously be required if CO_2 emissions are to be significantly reduced, it should be noted that the measures available for this purpose will differ from one country or region to another. It is suggested that any national or international programs to reduce CO_2 emissions be implemented in a flexible manner so that each country or region can use those measures which will be least disruptive to the local economy.

I. INTRODUCTION

Climatologists have been concerned for some time with the progressive increase in atmospheric concentrations of carbon dioxide and other infrared-absorbing gases, and with the global climatic changes that might result from "greenhouse warming." This concern has now spread to the public and political arenas, in part as a result of the droughts, floods, and unseasonable temperatures that have been experienced in many parts of the world in the past few years. While these are not blamed directly on greenhouse warming, they are often portrayed as a foretaste of what is to come if action is not taken to forestall a global warming trend.

Increased emissions of carbon dioxide are considered to be responsible for at least half of the absorption of re-radiated solar energy which gives rise to greenhouse warming, with the remainder due to methane, nitrous oxide, chlorofluorocarbons, and other materials. It should be noted that some of these other gases, particularly chlorofluorocarbons, are much stronger infrared absorbers on a molar basis than carbon dioxide, and since they are very long-lived, their contribution to greenhouse warming is expected to exceed that of carbon dioxide early in the next century if emissions are not reduced. However, there is general agreement that carbon dioxide is the main problem at the present time, and that combustion of fossil fuels is the largest man-made source of carbon dioxide. Land clearing has been variously estimated to contribute 10% to 40% as much carbon dioxide as fossil fuel burning. Consequently, it is usually concluded that a world-wide reduction in fossil fuel consumption will be an essential part of any strategy to avoid global atmospheric warming and the resulting disruption of agricultural production, flooding of costal regions, and other undesirable consequences.

On the other hand, the economic penalties and interference with national development programs that would be involved in any large scale switch away from fossil fuels suggests that the necessary global action is unlikely to be implemented quickly, even if there is a strong scientific consensus that the threat is real and urgent. This is particularly true as long as there is room for doubt as to the actual climatic changes that will take place in specific regions as a result of global warming. However, it is also possible that there will be pressure on developed countries to make proportionately larger reductions in carbon dioxide emissions to provide room for less-developed countries to increase their energy production.

Despite uncertainties as to the timing and extent of such action, the importance of the fossil fuel industry to Alberta is so great that it seems prudent to give some consideration to the effects on the provincial economy if fossil fuel production were seriously restricted, and more constructively, to the measures which might be taken to reduce the need for such restrictions. The following is a preliminary attempt at such a study, under the following headings:

1. The likely effects on the fossil fuel industry if an arbitrary reduction in fuel use were mandated by national or international policy, and the alternative forms of economic activity that might then be available to Alberta.
2. Possible ways of reducing the net emission of carbon dioxide to the atmosphere without reducing energy production from fossil fuels. Such measures could be used as justification for reducing or delaying restrictions on fossil fuel use.

II. ASSUMPTIONS USED IN STUDY

In view of the previously-mentioned difficulties in implementing a rapid reduction in fossil fuel usage world-wide, it is assumed that an attack on the greenhouse problem will involve a combination of the following:

1. A concerted effort to discourage forest clearing;
2. A ban on virtually all uses of chlorofluorocarbons;
3. A staged reduction in fossil fuel use.

The reductions in fossil fuel use would be made selectively to maximize the decrease in carbon dioxide emissions; the resulting shortfall in primary energy supply would be made up by increased energy conservation measures, and by increased use of nuclear energy and renewable energy (hydroelectric, biomass, wind, and direct solar energy). Most of these shifts to other energy sources will require long lead times or the development of new technology, providing a further "breathing space" for the fossil fuel industry.

III. EFFECTS OF A MANDATED REDUCTION IN FOSSIL FUEL USE

Since the purpose of curtailing fossil fuel use is to reduce carbon dioxide emissions, the realistic approach would be to make the greatest reduction in the use of fuels which produce the most carbon dioxide per unit of combustion energy, i.e. the hydrogen-deficient fuels such as coal and residual fuel oil. On the other hand, since natural gas only produces about half as much carbon dioxide per unit of combustion energy as coal, total carbon dioxide emissions could be reduced by substituting natural gas for coal or residual fuel oil wherever possible. This policy would also reduce acid rain and toxic metal emissions.

The likely effect of these considerations is that there will be strong pressure to phase out the use of coal for electric power generation, unless it proves economically feasible to convert the coal to a higher hydrogen/carbon ratio fuel or to remove carbon dioxide from the stack gases as discussed in Section IV. Non-fuel uses for coal such as iron and steel production will presumably continue until such time as hydrogen reduction processes become widely used.

In contrast, natural gas consumption for fuel use is likely to continue and expand both domestically and for export. Natural gas is also likely to be the preferred source of hydrogen by steam-methane reforming for some time to come, and the demand for hydrogen in nitrogen fertilizer manufacture, improving the hydrogen to carbon ratio of other fuels, in metallurgical processes, and for direct use as a fuel can be expected to increase. Hydrogen production by steam-methane reforming yields carbon dioxide as a by-product, but in the form of a concentrated stream which can be used for enhanced oil recovery or removed from the environment by long-term storage as discussed in Section IV.

Over-all, it seems likely that Alberta will be able to market all the natural gas it can produce, and at increasing prices.

The situation with respect to conventional and synthetic crude oil is less clear. The amount of carbon dioxide per unit of combustion energy is 25% to 30% less from liquid hydrocarbons than from coal, but the total amount of energy produced from petroleum products is so much greater than from coal in most parts of the world that they represent one of the largest sources of CO_2 emissions. Consequently, there will almost certainly be continued pressure to reduce oil consumption, both through more efficient use and through replacement by alternative fuels. However, as noted earlier, it is unlikely that the consumption of liquid hydrocarbon fuels can be decreased very rapidly even under a strict regulatory regime. Residual fuel oils are likely to be phased out as quickly as they can be replaced by natural gas or other energy sources, followed by furnace oils for domestic and commercial heating. On the other hand, transportation fuels such as gasoline, diesel fuel, and aviation fuel will require substantial changes in production facilities, distribution systems and end-use equipment before they can be replaced by non-fossil sources. This will require considerable time and capital investment, so there is likely to be a fairly long transition period in which liquid hydrocarbons will continue to be required on a decreasing scale.

Non-fuel uses of petroleum such as lubricants, paving materials, building products, and petrochemical feedstocks may be expected to continue and grow. In a non-fossil fuel economy, the main products of a refinery might be petrochemical feedstocks, solvents, lubricating oil stocks, waxes, and asphalt. This would be in line with the long range view that hydrocarbons are too valuable as a source of materials to be used for energy production. However, the medium-term effect on the oil industry would be a considerable decline in the demand for conventional and synthetic crude unless expanded markets could be found for non-fuel products.

The petrochemical industry is a major consumer of refinery products such as naphtha and BTX in many parts of the world. The petrochemical industry in Alberta is in a healthy condition and can almost certainly look forward to long-term growth as a result of its favorable raw materials situation. At present, petrochemical operations in Alberta are dominantly based on ethylene from ethane, which benefits natural gas production rather than oil. However, continued growth will probably require the Alberta industry to turn increasingly to LPG and naphtha cracking for ethylene as the available supplies of ethane become fully committed. The Alberta industry may also be able to diversify more extensively into products based on higher olefins and BTX such as elastomers and polyesters. Styrene monomer is already being produced at Scotford from benzene and ethylene, and the lighter fractions from conventional and synthetic crude refining which will be abundantly available if gasoline consumption decreases should offer economically attractive opportunities for producing many other petrochemical products.

Looking at possible economic opportunities outside the fossil fuel industry, Alberta will be in a favorable resource position to supply some of the proposed alternative fuels when and if renewable energy becomes widely used. Agricultural and forest products could be used to produce fermentation ethanol or syngas for fertilizer and methanol production. Alberta should be in a strong position to market methanol from renewable resources as an adjunct to its present dominant position in methanol production from natural gas. The availability of large tracts of range land in southern Alberta with high average wind speeds and high solar radiation should also make Alberta an attractive location for developing these energy sources when and as they become economically competitive.

In summary, the natural gas industry is likely to continue in a healthy state for a long period of time, both as the least-objectionable hydrocarbon fuel and as a source of hydrogen. The demand for natural gas and petroleum feedstocks for petrochemical manufacture will continue and grow, as should the non-fuel uses for conventional and synthetic crude oil. A concerted program of research and market studies should be able to identify increased opportunities in these non-fuel areas as a result of Alberta's favorable resource situation. Use of liquid hydrocarbons as transportation fuels will not stop abruptly because of the time required for changes in the fuel production, distribution, and end-use systems. However, there will eventually be a substantial and continuing decrease in markets for conventional and synthetic crude since non-fuel applications are likely to represent only a small part of the present production.

Direct combustion of coal for power generation might have to be considerably reduced, although there are other routes to using coal as discussed in the next section. Finally, Alberta could develop new economic activities related to alternate fuels and energy sources. If the present efforts to diversify the Alberta economy to reduce its vulnerability to changing world oil prices are maintained, it is likely that the effects of reduced demand for oil and coal will not be too serious, particularly if some of the measures suggested in the next section are also taken.

IV. REDUCTION OF CARBON DIOXIDE EMISSIONS FROM FOSSIL FUEL UTILIZATION

The estimated CO_2 emissions from fossil fuel production and utilization in Alberta are listed in the following tables by energy use sector and by type of fuel:

Table 1

CO_2 Emissions by Energy Use Sector (millions of tonnes per year)
(1 tonne = 537 cubic meters at 15°C)

Combustion of Fuel	
Residential	7.4
Commercial	4.8
Industrial	12.0
Transportation	16.6
Electric Power Generation	32.7
Sub-total	73.5
Production & Processing of Fuels (including pipelining and CO_2 originally present in natural gas)	37.3
Total	110.8

Table 2

CO_2 Emissions by Type of Fuel (millions of tonnes per year)

Natural Gas	51.0
Propane	1.3
Refined Petroleum Products	18.0
Process Fuels	9.0
Coal	31.5
Total	110.8

It might be noted that the energy-related emissions of CO_2 in Alberta are the highest per capita of any province in Canada, primarily as a result of two factors: the very high proportion of electricity generated from coal, and the fact that all of the CO_2 associated with production and processing of fuels is emitted within the province, even though four-fifths of the oil and natural gas are exported.

The net emissions of carbon dioxide to the atmosphere could, in principle, be reduced by one or a combination of the following methods:

1. Increasing the hydrogen to carbon (H/C) ratio of fuels so that the amount of carbon dioxide emitted for a given energy production is reduced. In order to be effective, the hydrogen required for this purpose must be produced by a method which does not itself add more carbon dioxide to the atmosphere than is saved by the increased H/C ratio of the fuel.
2. Reducing or capturing the carbon dioxide emitted during production, processing, and transportation of the fuel.
3. Capturing the carbon dioxide produced during combustion of the fuel and storing it for an indefinite period.
4. Growing vegetation to remove carbon dioxide from the atmosphere to yield a net reduction in carbon dioxide emissions from fuel burning.
5. Increasing the efficiency of fossil fuel utilization to decrease the quantity of fuel consumed for a given end result.
6. Reducing the emissions of carbon dioxide from sources other than fossil fuel combustion.

Each of these approaches will now be discussed in more detail.

1. Increasing the H/C Ratio of the Fuel

Fuels with a high ratio of hydrogen to carbon produce less carbon dioxide per unit of combustion energy than fuels with a low ratio. The carbon dioxide emissions in tonnes per terajoule range from slightly less than 50 for natural gas to 60 for propane or methanol, 67 for gasoline, 70 for fuel oil, 80 for oil sands bitumen and 90 to 95 for coal.

It is already standard practice to increase the H/C ratio of oil sands bitumen in the "upgrading" process to produce a light synthetic crude oil which is much easier to transport and refine than raw bitumen. Similarly, coal can be converted to liquid fuels, either alone or by co-processing with bitumen, or to a "substitute natural gas." These conversions are normally carried out to make the fuel more useful for its intended purpose, but they also have the effect of reducing carbon dioxide emissions for a given energy production. This is particularly so if the conversion is carried to the point where the end-product consists primarily of saturated hydrocarbons of relatively low molecular weight.

It should be noted that conversion of coal to liquid or gaseous fuels not only increases the H/C ratio, but also makes it possible to move the fuel to the point of consumption by pipeline instead of by rail or road transport. This in turn reduces the fuel consumed for transportation and the CO_2 emissions from this source. As a further bonus, air pollution will be greatly reduced when the fuels are burned since sulfur, nitrogen, and metals can be reduced to as low a level as required.

As mentioned earlier, this benefit is only obtained if the hydrogen required for hydrogen addition processes is obtained by some route which does not itself release more by-product CO_2 than the reduction in CO_2 emissions during combustion of the fuel. The only commercial method of generating hydrogen without by-product CO_2 is electrolysis of water, using hydroelectric or nuclear-generated electricity. Other possible routes are electrolysis of H_2S and thermal decomposition of water by one of the thermochemical cycles, again using non-fossil energy sources.

The other approach is to use conventional steam-methane reforming or oxygen gasification of coal as the source of hydrogen, and capture the by-product CO_2. This is technically quite feasible in these cases because the by-product CO_2 is obtained as a concentrated stream which minimizes recovery and compression costs. The CO_2 could be used for enhanced oil recovery or stored in underground reservoirs on a long-term basis.

It should be noted that a smaller but significant amount of CO_2 is produced in steam-methane reforming by the combustion of fuel in the reformer furnace. This only represents about 20% of the by-product CO_2 in processes designed to minimize external fuel requirements, but its capture is more difficult since it is diluted with nitrogen from the combustion air. A possible alternative might be the use of partial oxidation or other processes to eliminate external heat requirements.

There are also methods of producing fuels with increased H/C ratios without actually adding hydrogen. One of these is carbon rejection, which is the basis of the coking processes used for primary upgrading in the first two commercial oil sands plants. In this case, the by-product coke would either be stored indefinitely, or utilized in some fashion which did not release CO_2 to the atmosphere. While relatively simple, this route does not represent the most efficient utilization of liquid hydrocarbon resources and is unlikely to be favored as a long-term solution.

The other route is to produce syngas by steam-oxygen gasification of coal and convert it to methanol. As with

hydrogen production from coal, the by-product CO_2 would have to be recovered and stored. With this qualification, the use of methanol as fuel would reduce carbon dioxide emissions by about 21% on an equal energy basis compared to direct combustion of coal.

2. Reducing Carbon Dioxide Emissions during Production and Processing of the Fuel

The carbon dioxide emitted during production, processing, and transportation of fuel to the point of use can be a significant fraction of the carbon dioxide emitted during eventual combustion. These sources of CO_2 are particularly important in Alberta, since as noted earlier, four-fifths of the liquid fuels and natural gas produced in the province are burned elsewhere, but all of the CO_2 associated with their production is emitted within the province. Consequently, reducing these emissions can have a significant effect on the over-all environmental impact of the fossil fuels industry.

These carbon dioxide emissions can be considered under two headings: those associated with the provision of mechanical and thermal energy for mining, production, processing and transportation, and those associated with the upgrading or conversion process itself.

Mechanical energy is required for mining machinery and conveyors, well pumps, process equipment, gas compressors, pumping stations, and rail or road transportation of coal. Much of this equipment is electrically-powered, but in fuel-producing areas, the electricity is usually also generated by combustion of fossil fuels. Thermal energy is required for in-situ bitumen production, extraction of bitumen from mined oil sand, bitumen upgrading, and natural gas processing. This thermal energy is again obtained either directly or indirectly from combustion of fossil fuels.

The carbon dioxide emissions from electric power generation could be reduced by nearly 50% by using natural gas as fuel instead of coal or coke, or eliminated entirely by using hydroelectric energy. The carbon dioxide emissions from provision of heat energy could be reduced by using natural gas as fuel in the relatively few cases where coal or by-product coke is now used. In the important case of steam generation for in-situ bitumen production, CO_2 emissions can be minimized by using production processes with low steam/oil ratios such as underground access and gravity drainage.

Much of the carbon dioxide emitted from bitumen upgrading or coal conversion processes arises from hydrogen production by steam-methane reforming or partial oxidation of coal, coke, or residua. As discussed earlier, the by-product carbon dioxide is obtained in a concentrated stream from processes such as steam-methane reforming or oxygen gasification, so that it is technically feasible to collect and store it. Carbon dioxide is also emitted from combustion of coke in carbon- rejection processes. The minimization of CO_2 emissions from production of synthetic crude from oil sands bitumen was discussed in somewhat more detail in a paper presented at the 1983 Energy Opportunities Conference in Edmonton.

An indirect method of reducing carbon dioxide emissions is to use high-conversion upgrading processes so that the yield of desired products obtained from a given quantity of feed is maximized. Since many of the energy inputs are proportional to the feed rate, this means that the carbon dioxide emissions for a given energy output are also reduced.

In the case of natural gas processing, some 8% of the total marketable gas is burned for process heat, resulting in the emission of nearly 12 million tonnes per year of CO_2. Possible methods of reducing these emissions are the use of more energy-efficient processes and the recovery of dilute CO_2 from flue gas.

Most of the natural gas produced in Alberta also contains some CO_2 in the raw gas which is removed along with H_2S in the gas sweetening process and subsequently discharged to the atmosphere in the tail gas from the Claus plants. The total quantity of CO_2 from this source is of the order of 5 million tonnes per year, and would represent a worthwhile reduction if it could be captured economically. The CO_2 and H_2S are obtained as a concentrated stream from the acid gas removal process, and might be separated by solvent or selective permeation methods. The alternative route of recovering CO_2 from the tail gas will probably be more costly because the CO_2 is diluted by the nitrogen from the combustion air.

It should be noted that the total CO_2 emissions involved in the processing of natural gas represent 15% or more of the CO_2 emitted when the gas is eventually burned, which is a considerably higher percentage than in the case of coal. It is therefore important to develop methods of reducing these emissions if the maximum benefits are to be obtained from the replacement of coal by natural gas.

In summary, a reduction in the amount of carbon dioxide emitted during production, processing, and transportation of a fuel can represent a significant reduction in the total CO_2 emissions associated with the use of fossil fuels. The means available for reducing carbon dioxide emissions include the use of processes with improved energy efficiency, the substitution of natural gas for coal or coke, the use of hydroelectric power (perhaps imported from British Columbia or Manitoba), the capture of by-product CO_2 from hydrogen production, and the use of high-conversion bitumen upgrading processes.

3. Capturing Carbon Dioxide from Fuel Combustion

This approach will probably only be feasible for large stationary sources since it is difficult to visualize chemical absorption or physical adsorption systems small and rugged enough for motor vehicles or even for domestic heating systems, except perhaps in the form of replaceable cartridges which could be regenerated at a central facility. However, industry and electric power plants represent more than two-thirds of CO_2 emissions from fuel production and use in Alberta, and constitute a worthwhile target.

The carbon dioxide content of flue gas ranges from about 8% by volume for natural gas fired furnaces to 14% for

coal fired furnaces. This carbon dioxide may be removed from the flue gas and recovered as a high-purity stream using modified versions of the alkanolamine or hot carbonate processes normally used for natural gas processing. Several commercial plants using these processes have been constructed to produce carbon dioxide for enhanced oil recovery from natural gas fired power stations.

It has been suggested that the same processes could be used to reduce atmospheric emissions from power stations and industrial plants by recovering the CO_2 and removing it from circulation by placing it in some form of long-term storage. In coastal regions, the recovered CO_2 could be discharged into deep ocean water through pipelines on the sea bottom, where the high solubility at elevated pressures and the resulting increased density of the solution would inhibit migration back to the surface. In Alberta, a substantial part of the recovered CO_2 could be utilized productively for enhanced oil recovery (EOR), while the remainder could be stored in depleted reservoirs or salt caverns. Underground storage could also be used in most other regions with large sedimentary basins.

The principal impediments to this solution to the CO_2 emission problem are the high capital costs and energy consumption of the recovery process. Costs of recovering CO_2 by this route are generally competitive with other sources of high-purity CO_2 when the CO_2 is the desired product, but impose a heavy economic penalty on a power station when the CO_2 is a waste product requiring disposal. The processes that were considered in 1982 for recovering CO_2 from coal-fired electric generating plants for EOR purposes would add about 5 cents per KWH to the cost of power generation, neglecting CO_2 disposal costs. The most economical processes reported in the literature for recovery of CO_2 from natural gas fired power stations would add about 2 1/2 cents per KWH, but additional costs for gas cleaning and solvent make-up would be involved if they were applied to coal-fired power stations.

The high capital cost arises mainly from the large equipment required to cool, clean and circulate the flue gas and to absorb CO_2 at the low concentrations present. Solvent make-up or reconditioning costs are also significant as a result of irreversible reactions between sulfur and nitrogen oxides in the flue gas and the absorbing solvent. The energy requirements are primarily in the form of heat for regenerating the absorbing solution. The amount of heat required depends on the concentration of CO_2 that can be reached in the solution leaving the absorber, which in turn is limited by the pressure and CO_2 concentration of the flue gas, by corrosion problems, and other factors. In some of the earlier systems, the heat required for regeneration would represent half or more of the total heat output of the power plant boilers, although at a relatively low temperature.

Low pressure steam for regeneration may be available in process plants from other parts of the process, but in the case of a thermal power plant, it would usually be necessary to obtain the steam from back-pressure turbines with a consequent loss of thermal efficiency. The cost of electric power generation with carbon dioxide recovery will therefore be increased by the cost of the recovery process itself and also by the reduced amount of electrical power generated from a given fuel input and plant capacity.

The cost penalty involved in removing CO_2 from power plant flue gas would be considerably reduced if

consumptive, revenue-producing uses could be found for a major part of the recovered carbon dioxide. The familiar uses of carbon dioxide in carbonated beverages, as dry ice, as an aerosol propellant, and as a fire extinguishing agent are non-consumptive, while enhanced oil recovery is only consumptive in the long run to the extent that carbon dioxide is left in the reservoirs at the completion of the projects. The chemical uses of carbon dioxide appear to be very few compared to carbon monoxide, and the CO_2 is often produced elsewhere in the process. The Solvay process for manufacture of sodium carbonate from common salt uses large amounts of carbon dioxide, but the lime required to regenerate ammonia and tie up the chloride ion as calcium chloride is obtained by calcination of limestone, which provides all the required carbon dioxide. In any case, the Solvay process has been largely replaced by natural soda production in North America. A literature search and possibly some exploratory research to find new uses for CO_2 might be justified.

In principle, carbon dioxide could be thermally dissociated or reduced with hydrogen to produce carbon monoxide for production of polycarbonates, polyurethanes and other plastics. However, these reactions are energetically very unfavorable and it would be necessary to use a non-fossil energy source, so it is likely that this would be a more expensive method of disposing of carbon dioxide than storage. A more practical method would be to utilize solar energy to convert carbon dioxide to plant material by photosynthesis, as discussed in the next section.

The capture of CO_2 from flue gas would be greatly facilitated if the combustion were carried out with oxygen instead of air, so that the flue gas could be compressed and injected directly into a reservoir. The elimination of the absorption and regeneration processes should more than compensate for the cost of oxygen production by air separation. The oxygen might be diluted with recycled combustion gas if needed to control flame temperature, and it might also be advantageous to carry out the combustion at somewhat elevated pressure.

Combustion with oxygen under pressure would require the complete replacement of the conventional boiler furnace, and would probably be most practical with liquid and gaseous fuels. However, coal could be converted to fuel gas by steam-oxygen gasification and burned without preliminary removal of the by-product CO_2. As a result of the high combustion temperatures, the hot gases could be advantageously used in a combined-cycle (gas turbine and steam boiler) generating plant and perhaps eventually in a MHD generator.

4. Growing Vegetation to Remove CO_2 from the Atmosphere

The growth of vegetation provides an apparently "free" solution to the carbon dioxide problem by converting carbon dioxide into cellulose and other organic compounds by photosynthesis, using sunlight as the energy source and releasing oxygen in the process. It would be possible to visualize direct capture of carbon dioxide from thermal power plants by leading the flue gas into enormous greenhouses, using the condenser cooling water from the plant to maintain growth temperature at a suitable level year-round. However, a more immediately practical solution would be to encourage the natural growth of vegetation to absorb carbon dioxide from the atmosphere and produce a net decrease in carbon dioxide emissions.

It must be noted that the growth of vegetation only removes carbon dioxide from the atmosphere as long as there is a net accumulation of biomass, i.e., the rate of growth exceeds the rate of decay. Consequently, a mature forest removes very little carbon dioxide from the atmosphere since there is no further net accumulation of biomass apart from a small amount laid down as peat and other humic materials. The maximum benefit from growth of vegetation is obtained by harvesting the trees or other crop when the growth rate starts to decline, and immediately starting new growth. The wood or other plant material must then be utilized as fully as possible in ways that avoid returning carbon dioxide to the atmosphere for a long period, e.g., by use as building materials. Fuel or food uses obviously defeat the purpose of the exercise, except to the extent that they replace fossil fuel-derived products for the same use, as in the case of fuel ethanol.

Despite these limitations, re-establishment of long-lived vegetation such as trees on ground which is currently unproductive or used for annual crops will produce a net removal of carbon dioxide from the atmosphere over the 50 years or more while the trees are still growing. This may well span the time frame until other energy sources begin to supplant fossil fuels for technical or economic reasons. Even when reforestation is not feasible, the burning of trees for land clearing should be discouraged as much as possible. The latter practice returns all the stored carbon compounds to the atmosphere as carbon dioxide without using their fuel value to reduce fossil fuel combustion.

In Alberta, there are large areas which are marginal or submarginal for agricultural purposes other than grazing land. An aggressive program of tree re-growth might provide a credible argument for easing restrictions on fossil fuel use in recognition of the compensating removal of CO_2 from the atmosphere. Further study would be required to determine whether it would be more effective to plant long-lived tree species, or rapidly-growing species which would be harvested periodically and as much as possible of the plant material put to long-lived uses. The amounts of land required are not small: a rough estimate indicates that about 50,000 square kilometers, or 7% of the province's total land area, would be required to absorb the CO_2 from the coal burning power plants of Alberta.

5. Increasing the Efficiency of Energy Utilization

Reducing CO_2 emissions by more efficient utilization of energy might be seen as having a negative effect on the fossil fuels industry, since unlike the other measures discussed in this section, the reduction in CO_2 emissions is obtained by reducing fuel consumption. However, efficient energy utilization will almost certainly be a part of any over-all strategy for reducing CO_2 emissions, since it will often be the least costly approach and will also be encouraged as a conservation measure. From the standpoint of this study, efficient energy utilization will provide an added justification for continuing the use of fossil fuels, even if at a reduced rate.

Efficient energy utilization has been the subject of many studies and programs since the oil price and supply panic of the 1970's, and considerable progress has been made in reducing energy consumption through such measures as increased insulation and improved energy management in buildings, fuel-efficient vehicles, and replacement of

older equipment with new equipment designed for higher energy efficiency. However, a recent discussion paper by the Conservation Branch of Alberta Energy suggests that there is potential for a further reduction of 11% in fuel consumption and 17% in electricity consumption in the residential sector, of 24% and 13% respectively in the commercial sector, of 21% and 9% in the industrial sector, and of 20% in fuel consumption in transportation. If attained, this would represent an over-all reduction of 15% in fuel consumption and of 10 million tonnes per year in CO_2 emissions.

Substantial energy savings are often possible in the chemical and process industries through energy integration and by appropriate choice of energy sources so that high grade energy is used only where actually needed and lower grade or by-product energy is used elsewhere. In particular, electric energy would only be used for production of mechanical energy and for lighting and control applications, while thermal energy would be obtained by combustion of fuel or as waste heat from other operations. Contrary to some popular impressions, the replacement of fuels by electricity would increase rather than decrease CO_2 emissions, since most of the electricity in Alberta is itself generated from fuels at much lower conversion efficiency than production of heat by direct combustion of fuel.

There might appear to be a great deal of scope for reducing CO_2 emissions by improving the conversion efficiency from fuel energy to electrical energy, since electric power generation is responsible for nearly 45% of all CO_2 emissions from fuel combustion in Alberta, and the annual average conversion efficiency for all power stations is about 31%. However, any significant increase in the efficiency of existing generating stations would require almost complete rebuilding to convert to higher steam temperatures, and even then the average efficiency would probably not exceed 35% to 36% under actual operating conditions.

Further increases in conversion efficiency will either require working fluid temperatures much higher than those possible with steam boilers and turbines, or an energy conversion method which avoids thermodynamic cycle limitations. The most practical method of exploiting high working fluid temperatures is to burn the fuel in a combustion turbine,which can accept inlet temperatures up to 1100°C compared to about 550°C for a steam turbine. The thermal efficiency of the combustion turbine itself is only 25% to 30%, but this can be increased to 40% or more by generating steam from the hot exhaust gas in a "combined cycle"plant. Integrated coal gasification-combined cycle (IGCC) plants which utilize the sensible heat of the fuel gas can have conversion efficiencies as high as 42%.

Two methods currently being developed which avoid thermodynamic cycle limitations in generation of electricity are fuel cells and magnetohydrodynamic (MHD) generation. Fuel cells of relatively low power output have been used successfully for some time in applications which take advantage of their special characteristics such as the absence of moving parts, and an 11 MW prototype unit for power station use is expected to be operational in 1990. The conversion efficiencies that can be attained with fuel cells are considerably higher than with conventional methods of electric power generation, and the reasons they have not been used on a larger scale to date have

probably involved a combination of higher capital and maintenance costs, the lack of long-term operating experience, and the requirement for hydrogen as fuel. This latter requirement makes fuel cells a "natural" for a hydrogen economy, but introduces added costs and energy losses in converting fossil fuels to hydrogen. Relatively pure hydrogen is required for low temperature fuel cells, although high temperature cells of the molten carbonate or solid oxide types can utilize a mixture of carbon monoxide and hydrogen, eliminating the shift conversion step. The over-all conversion efficiencies from natural gas or coal to electricity can be slightly over 40% with phosphoric acid fuel cells and 50% to as much as 55% with molten carbonate cells and co-generation of electricity from waste heat.

Conversion efficiencies of MHD generators are typically of the order of 40%, which can be increased to 50% or 55% by generating steam from the hot exhaust gas for additional electricity production. However, MHD generation still faces major technical problems and is not expected to reach commercialization before the turn of the century.

In summary, there appear to be opportunities to reduce CO_2 emissions by about 10 million tonnes per year in Alberta through the use of fairly straightforward energy conservation measures, although some of these may require additional incentives at current energy prices. There are probably also some further opportunities for reducing energy consumption in process plants through improved "second law efficiency." The production of electricity in thermal power stations is an attractive target for increased efficiency in principle, but any major improvement will require the replacement of steam turbine power plants by other generating methods at very high capital costs.

Combined cycle generation has the potential for a decrease of about 5% in fuel consumption over conventional power stations. It is possible that integrated coal gasification-combined cycle plants will be constructed as a adjunct to existing coal-fired power plants in any case, primarily to take advantage of their ability to adjust rapidly to changing loads for "peak shaving." If so, this will provide operating experience which may lead to wider use for base load generation.

Any further large increase in fuel economy will require the use of fuel cells, assuming that MHD generation is still some distance in the future. Even fuel cells in capacities suitable for power plant use are unlikely to have been demonstrated in long-term operation much before the end of the century, although their prospects for success seem high. Their first commercial uses will probably come in decentralized power generation and in load levelling applications, where their insensitivity to economies of scale and their relatively constant efficiency under varying loads are added advantages.

Viewed solely from the standpoint of conversion efficiency, the use of fuel cells in place of conventional steam turbine plants would reduce fuel consumption by 20% to 35% and CO_2 emissions by 7 to 12 million tonnes per year. However, this represents only part of the benefits from fuel cell use, since they would facilitate CO_2 capture as well as reducing the amount produced. A fuel cell operating on hydrogen will obviously produce no CO_2 itself, and the by-product CO_2 from the conversion of fossil fuels to hydrogen is obtained as a concentrated stream which can be recovered for storage or use as described in part 1 of this section. High temperature fuel cells capable of

utilizing carbon monoxide and hydrogen could be operated with oxygen instead of air, yielding an exhaust stream of CO_2 and water vapor which could again be recovered readily.

6. Reduction of CO_2 Emissions from Sources other than Fossil Fuels

There are many natural and man-made sources of atmospheric CO_2 apart from fossil fuel combustion, and any significant decrease in emissions from these sources would provide "room" for additional fossil fuel use. Some of the more important sources in Alberta are shown in the following table:

Table 3

CO_2 Emissions from Non-Fossil Fuel Sources

(millions of tonnes per year)

Industrial Sources	
Ammonia Production	1
Lime and Portland Cement Production	0.5
Other Man-Made Sources	
Waste Burning	2 – 5
Natural Sources	
Decay of Plant Material and Decomposition of Soil Organic Material	300 – 500
Forest Fires (10-year average)	8 – 10
Human and Animal Respiration	15 – 18

Ammonia production from natural gas yields by-product CO_2 in a concentrated form which is readily recoverable for use or disposal, and most of this is emitted from only two fertilizer plants in Alberta since the others convert much of their CO_2 to urea. Lime and Portland cement production give rise to by-product CO_2 from the calcination of limestone, but in these cases the CO_2 is diluted with combustion gases and will be more expensive to recover. The CO_2 emissions from natural sources shown in the table are extremely rough estimates, but serve to illustrate that the CO_2 released by slow oxidation of plant material is much greater than from combustion of fossil fuels. Large quantities of methane, another "greenhouse gas" are produced by anaerobic decomposition of plant material. Collectively, these emissions represent the recycling of most of the carbon that was originally fixed by photosynthesis. While extremely large, these sources of CO_2 are also widely dispersed so that the opportunities for capture or control are very limited. Probably the greatest opportunity lies in utilizing agricultural and forestry wastes for production of useful energy, rather than allowing them to decompose or burning them in the open. This might be done either by converting them to biomass fuels such as alcohols or fuel gas, or by burning them on-site for electricity production. Various estimates have suggested that 35% to 45% of Canada's total energy requirements could be met from agricultural and forest wastes, and the proportion should be at least this high for Alberta.

However, a practical limit will be set by the cost of collecting and transporting the waste material, and the best opportunities will arise when this is already being done in connection with forest products or agricultural processing operations. Even then, a 1981 study for Alberta Energy and Natural Resources indicated that about a million tonnes of sawmill waste was produced annually in Alberta, but that only 300 thousand tonnes of this was concentrated in large enough quantities to be economic for electricity generation. This quantity of sawmill waste would produce less than 2% of Alberta's electric power requirements, but would still eliminate about 0.5 million tons of CO_2 annually by reducing the amount of electricity generated from coal.

The current expansion of Alberta's forest industries should greatly increase the quantity of mill wastes beyond that available in 1981, and some of the other methods of waste utilization may be economically viable on a smaller scale than electric power generation. Large quantities of agricultural wastes also accumulate at particular locations and could be used to produce such fuels as ethanol and "biogas." Over-all, it seems probable that energy and biomass fuels equivalent to several million tonnes of CO_2 annually could be produced from agricultural and forestry wastes with current technology. This level of production would represent a significant component of the biomass fuels program discussed in Section III as an alternative form of economic activity for Alberta, although such a program would also include wood and agricultural crops deliberately grown and harvested for conversion to fuel. In all cases, it must be kept in mind that a reduction in CO_2 emissions through the use of biomass fuels is obtained at the direct expense of a reduction in fossil fuel use.

The quantity of standing timber burned in forest fires can be reduced on a long-term average basis through improved fire control measures, with economic benefits to the forest industries as well as reduced CO_2 emissions. Considerable progress is already being made in this direction in Alberta, although it might be noted that the task will be more difficult if greenhouse warming leads to hotter and drier summers as often predicted. Municipal waste burning has been largely replaced by landfill disposal to reduce air pollution, with the result that CO_2 and methane are only slowly released to the atmosphere. The burning of brush from land clearing is still practiced in parts of Alberta, and could be discouraged if the CO_2 emissions from this source are considered large enough to justify action.

The quantity of CO_2 produced by human and animal respiration is quite significant if the estimate shown in the table is valid, although the opportunities for capture are obviously limited and the costs may be disproportionately high. As one possibility, CO_2 might be recovered from recirculated ventilating air in office and institutional buildings in conjunction with other measures to improve indoor air quality. The total CO_2 production by farm animals is much greater than by humans in Alberta, and recovery might be feasible where large numbers of animals or poultry are housed in buildings with mechanical ventilation.

V. CONCLUDING COMMENTS

A few general observations can be made following this preliminary review. There is a growing consensus that the risk of global climatic changes from greenhouse warming is real and serious. These changes may not fully manifest

themselves for 25 to 50 years, but by this time it may be too late to implement measures to slow or reverse the climatic effects.

There are still differences of opinion as to the measures that should be taken in the meantime. Because of the political and economic difficulties of implementing world-wide action to reduce the accumulation of greenhouse gases, some agencies are looking at the changes in agricultural and other activities that will be required to accommodate to temperature and rainfall changes. On the other hand, many groups feel that measures should be taken now to avoid or minimize climatic change, and are proposing courses of action which range from a reduction of 50% or more in fossil fuel use to a combination of energy conservation, fuel substitution, a ban on chlorofluorocarbon use, and discouragement of land clearing by burning.

In the quite possible situation where international agreements and national policies call for a major reduction in CO_2 emissions, Alberta's fossil fuels industries would certainly be affected but not overnight and by no means fatally. A major switch to non-fossil energy sources cannot be implemented rapidly world-wide, even with full political agreement, because of the costs and time required for major changes in the production, distribution, and end-use systems. In any case, much of the reduction in CO_2 emissions will probably be brought about through conversion to fuels which produce less CO_2 per unit of energy, rather than by elimination of fossil fuels. This would lead to an increase in demand for Alberta natural gas and light synthetic fuels, although at the expense of coal and conventional crude unless other measures were taken to preserve markets for these fuels.

One such measure would be to develop new or expanded non-fuel markets for hydrocarbons, such as plastics and other organic chemical products, road and building materials, and lubricants. Alberta would also be in a favorable position to develop some of the renewable energy sources as an alternative form of economic activity, although this would not benefit the fossil fuel industry itself.

The other approach explored in this study is to reduce the environmental impact of fossil fuel use, both by minimizing CO_2 emissions to the atmosphere and by removing CO_2 from the atmosphere. The feasibility of the various measures that might be used varies very widely at the present stage of technology development. Processes for increasing the H/C ratio of fuels are in commercial use or at the demonstration stage for oil sands bitumen. Processes for converting coal to liquid fuels and substitute natural gas are technically proven and are mainly held back by economics in most parts of the world. The capture of CO_2 from high-concentration sources such as steam-methane reforming involves little more than gas compression, and will probably be done under normal market forces if the demand for CO_2 for enhanced oil recovery develops as projected. In contrast, recovery of CO_2 from power plant flue gas is costly and energy-inefficient with current technology.

Many of the measures considered in this study for reduction of CO_2 emissions rely on long-term underground storage of recovered CO_2. The information available to date suggests that such storage is technically feasible, safe, and effective; that abundant storage capacity is available, not only in Alberta but in much of Western Canada and

probably also some other parts of the country; and that the energy required for CO_2 compression and pipelining is a small fraction of the combustion energy of the fuel in many cases. However, it is clearly necessary to verify these indications and to determine the practical range of applicability of this approach to CO_2 emission control.

There are a number of other areas where literature surveys and research might lead to improvements in the technical and economic feasibility of the proposed measures to reduce net CO_2 emissions from fossil fuel use:

— Improved methods of production, distribution and utilization of hydrogen for upgrading of fossil fuels (as already visualized under the Alberta Hydrogen Program).
— Identification of stand-alone processes for production of hydrogen from natural gas and other hydrocarbons which eliminate dilute CO_2 emissions from fuel-fired heaters.
— Methods of decreasing fuel consumption in gas processing plants.
— Identification of most economical processes for separating CO_2 from H_2S in gas processing plants.
— More economical and energy-efficient methods of recovering CO_2 from flue gas.
— Development of small, regenerable CO_2 absorbers for vehicle exhaust and domestic furnaces.
— Development of oxygen combustion systems to facilitate recovery of CO_2 from flue gas.
— Identification of consumptive uses for CO_2 to reduce the net cost of recovery.
— The most effective methods of utilizing vegetation growth to remove CO_2 from the atmosphere, including the subsequent disposal of the plant material.

This study has been based on very approximate estimates in many cases, and requires substantiation with considerably more data before any specific courses of action are planned. The costs of the suggested measures for reducing net emissions of CO_2 have only been addressed in a few cases, but most of them will be clearly uneconomic at present energy prices. However, it should be noted that any forced reduction in fossil fuel use will automatically lead to higher energy costs, both through conversion costs and the fact that the fuels now used have normally been chosen as the least-cost alternatives. Consequently, some of the proposed measures to extend the acceptability of fossil fuels may be expected to become economic in a higher cost regime.

While it is difficult at this point to predict what form any national or international policies to reduce carbon dioxide emissions will actually take, the measures suggested in this study would provide sufficient flexibility to react to almost any scenario. Even in the extreme — and unlikely — case of a complete ban on fossil fuel combustion, with only hydrogen and biomass fuels permitted, Alberta would by no means be left out of the picture. Natural gas would be used to produce hydrogen with capture of the by-product CO_2, non-fuel uses of hydrocarbons could be expanded, and Alberta could move into the production of biomass-derived fuels. With more moderate scenarios a variety of options would be available for all sectors of the industry, as shown in the flow charts in Appendix 1.

Control of carbon dioxide emissions will obviously be a global challenge rather than just an Alberta problem, and it is important to recognize that not all of the measures discussed in this study will be viable options in all parts of the world. In particular, long-term storage of CO_2 in underground reservoirs will only be feasible in areas with large

sedimentary basins, and reforestation opportunities will be very limited in countries with high ratios of population to arable land area. On the other hand, these regions may have options which are unavailable or unacceptable for social or economic reasons in Alberta. Consequently, it will be highly desirable to implement any control policies in a flexible manner so that each country or region is free to develop its own strategy for bringing about an agreed reduction in CO_2 emissions. Taking Canada as an example, Quebec would probably prefer to increase its use of hydroelectric energy, Ontario to develop its nuclear industry further, and Western Canada to go to the trouble of reducing CO_2 emissions from fossil fuel use in order to preserve this industry. Vehicle users in all regions will probably wish to retain the convenience of liquid hydrocarbon fuels as long as possible and make their CO_2 reductions in other ways. Such a flexible policy would avoid unnecessary damage to regional economies and also eliminate the need to designate any particular energy source as the major villain. This may, in fact, be the only basis on which global agreement can be obtained for a reduction in CO_2 emissions.

Appendix 1

Selection Of CO_2 Reduction Options

The options available for reducing CO_2 emissions while continuing to use fossil fuels will depend on the forms in which energy is required and on the nature and severity of the restrictions which may be imposed on fossil fuel use.

The three basic forms in which energy is required are heat (for space heating, water heating, and process heat); electricity (for local conversion to mechanical energy, light, and heat); and mechanical energy for transportation and other mobile applications. These forms of energy can, in principle, be produced from any primary energy source although the costs and conversion efficiencies will vary widely. However, in the important case of mechanical energy for mobile applications, a readily-storable energy source is normally required, the role which is currently filled by liquid hydrocarbons.

The restrictions which might be imposed on fossil fuel use could take a number of forms. The most extreme course of action would be an outright ban on fossil fuel combustion; this is often interpreted as meaning that the only permissible energy sources would be nuclear energy and renewable energy(mainly hydroelectric, biomass, wind, and direct solar). Electricity would be generated from nuclear and hydroelectric sources, and to a lesser extent from combustion of biomass fuels and by wind and photovoltaic generation. The principal transportation fuels would be methanol and ethanol from biomass, and "neat" hydrogen. Increased use would also be made of storage battery electric vehicles.

Under this regime, hydrogen would be much used as a fuel for engines, for generation of electricity by fuel cells, and as a replacement for natural gas in domestic and commercial heating applications.

Even with a total ban on fossil fuel combustion, there is no logical reason why part or all of this hydrogen could not be produced from fossil fuels as long as the by-product CO_2 is captured and stored. Any of the fossil fuels can be converted to hydrogen as indicated in the flow sheets in Figs. 1-1 to 1-4.

A more probable scenario is a requirement for a progressive reduction in combustion emissions of CO_2 by definite percentages in specified periods of time. The required reductions might be expressed in either of two ways: specified reductions in fossil fuel use, or specified reductions in CO_2 emissions.

In the first approach, limits would be placed on the amounts of fossil fuels which could be used for energy production in each region, with the strictest limits on fuels which produce the largest amounts of CO_2 per unit of combustion energy. This approach would favor energy conservation, the substitution of natural gas for other fuels, and the conversion of coal, bitumen, and heavy fractions of conventional crude to fuels with high H/C ratios.

In the second approach, a given percentage reduction in the present CO_2 emissions would be mandated without specifying how this should be attained. Any combination of measures could be used, including conversion to higher H/C ratios, reduction of emissions from fuel production and processing, capture and storage of CO_2, increased efficiency of energy utilization, reforestation, and increased use of non-fossil energy sources. This approach would be the least disruptive of the three cases considered, and would probably be equally effective in attaining the desired result within a given period of time.

The preceding outline has dealt with the energy options that are technically possible under various regulatory regimes. There are other factors which will influence the actual choice of options, particularly economic impact, compatibility with existing infrastructure, and public acceptability. The economic analysis should take into account the over-all effects of a particular course of action on the provincial economy and the effects of different regulatory regimes on energy prices, as well as the comparative economics of alternative methods of reducing CO_2 emissions. A continuing effort will probably be required in this area as policies and technology evolve.

Any change in the present energy mix will cause some dislocation in the fuel distribution and end-use systems, but it will clearly be advantageous to adopt alternate energy sources which can make as much use as possible of the existing natural gas and liquid fuel distribution network. Similarly, the proportion of the total energy requirements met by electricity should be changed no more than necessary.

Societal attitudes toward various energy sources are often strongly held, but also tend to differ from one area to another and to change with time. It should be noted that <u>all</u> energy sources will involve some objectionable features when developed on a large enough scale to meet a significant fraction of total energy needs.

The options available for reducing CO_2 emissions from the major fuels produced in Alberta (coal, oil sands bitumen, conventional crude oil, and natural gas) are shown in flow-chart form in Figures 1-1 through 1-4. The options for meeting the fuel requirements of the electricity generating, transportation, and residential, commercial and industrial sectors with reduced CO_2 emissions are shown in Figures 1-5, 1-6, and 1-7, respectively.

Electricity generation is the largest single source of CO_2 emissions in Alberta, primarily because most of the electricity in the province is produced from coal. As indicated in Fig. 1-5, a number of options are available for reducing CO_2 emissions; reduced consumption of electric power through more efficient utilization; the use of higher H/C ratio fuels through fuel substitution or fuel conversion; capture of CO_2 from combustion; more efficient conversion of fuel to electric energy; and substitution of renewable energy for fuel energy. In this and other fuel use sectors, options should be selected which yield the required reduction in CO_2 emissions at the lowest over-all cost to the provincial economy, modified as necessary by public policy.

Transportation is the energy-use sector which produces the second largest CO_2 emissions, and the options for reducing these emissions are in turn limited by the required characteristics of a motor fuel and the doubtful

feasibility of capturing CO_2 from vehicle exhaust. The reductions in CO_2 emissions by increased H/C ratios in the options shown in Fig. 1-6 can be fairly accurately summarized as being inversely proportional to the convenience of use. The greatest reduction is obtained by converting other fuels to hydrogen with by-product CO_2 capture, but the use of hydrogen as a fuel for road vehicles is complicated by its very low boiling point and low volumetric energy density. The resulting storage and handling problems are being addressed through programs designed to promote the use of hydrogen from non-fossil sources as a universal fuel. The second-largest reduction in CO_2 emissions is provided by compressed natural gas (CNG), which requires high pressure refuelling and on-board storage, but which is being used successfully in fleet applications. In contrast, liquid fuels with properties comparable to conventional motor fuels produce only small reductions in CO_2 emissions. The sole exception is provided by ethanol and other biomass-derived fuels, which produce zero net emissions of CO_2 as long as no fossil fuels are used in harvesting and processing.

In the residential, commercial, and industrial sectors, 50% to 70% of total energy requirements are provided by direct combustion of fuels in Alberta, with essentially all of the remainder by electricity. In this instance the options for reducing CO_2 emissions from fuel combustion are somewhat limited by the fact that 93 – 94% of the fuel used in each of these sectors is natural gas, and the only practical fuel with a higher H/C ratio is hydrogen itself. Reduced fuel consumption by more efficient energy use, capture of CO_2 from large combustion sources, and the use of non-fossil energy sources are the other major options.

Methods of estimating the reductions in CO_2 emissions that may be obtained through the use of the various measures outlined in the study are described in Appendix 2.

Figure 1 - 1. Options for Reducing CO_2 Emissions from Coal Use

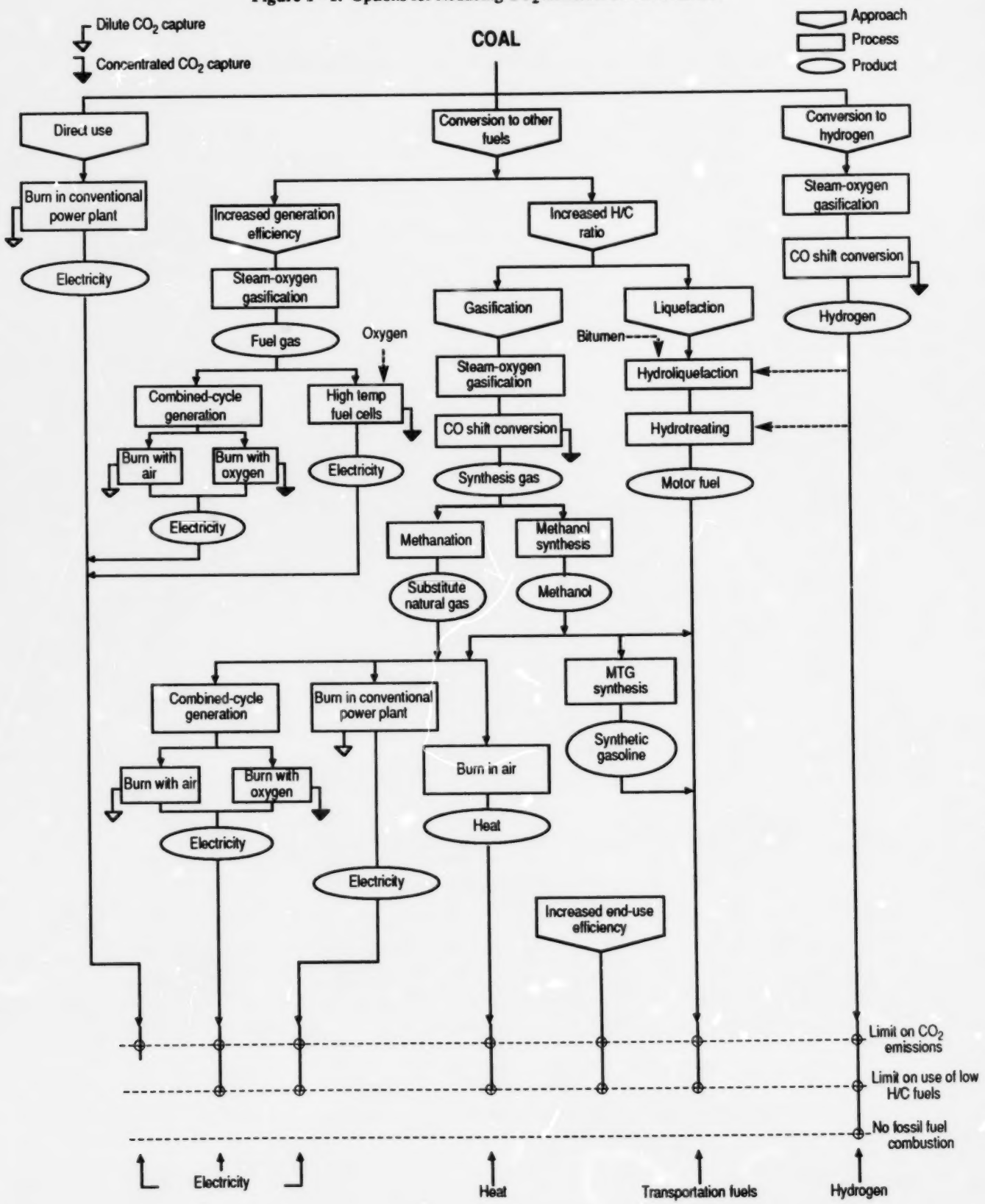


Figure 1 - 2. Options for Reducing CO_2 Emissions from Oil Sands Bitumen Use

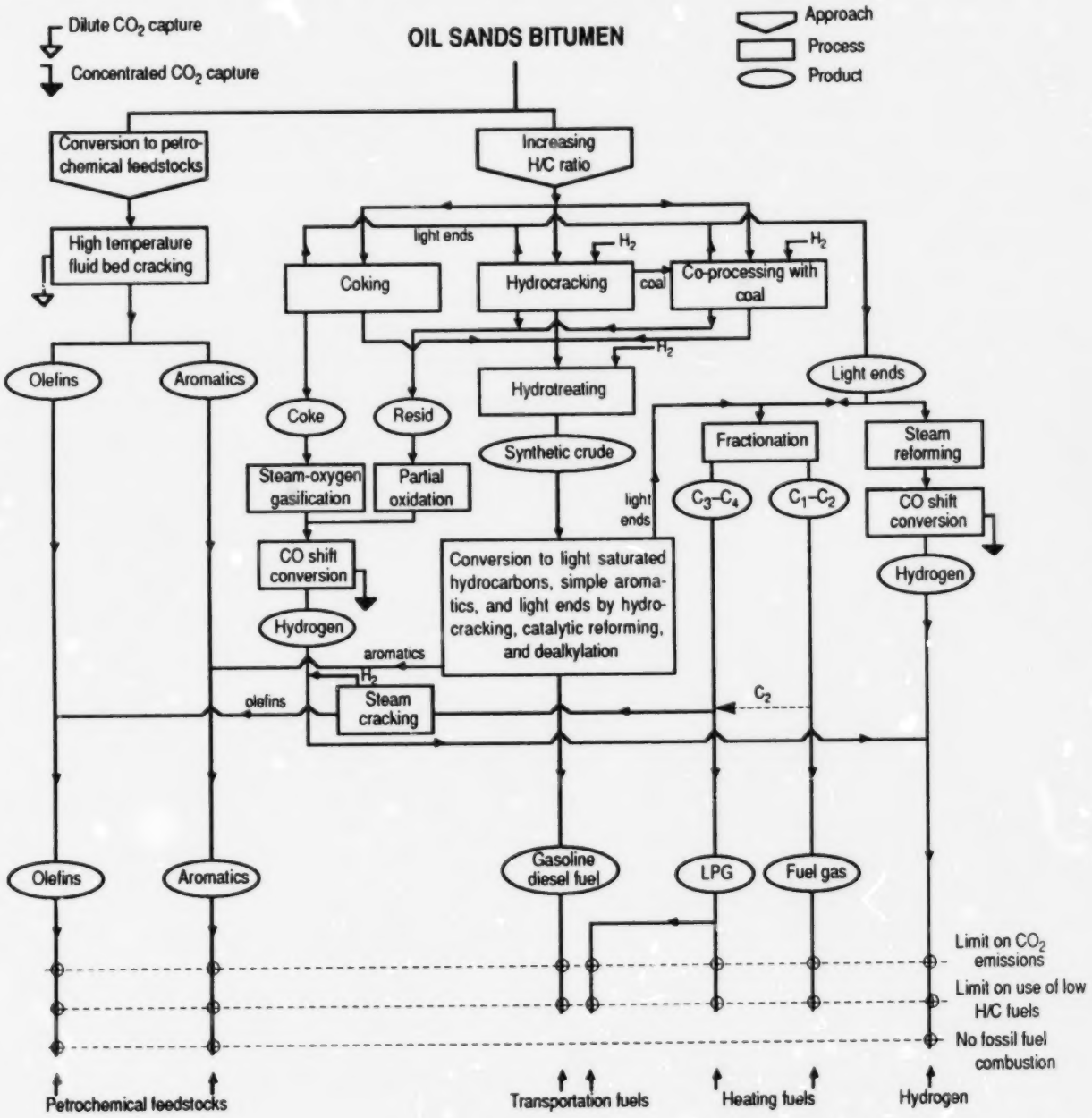


Figure 1-3. Options for Reducing CO_2 Emissions from Conventional Crude Oil Use

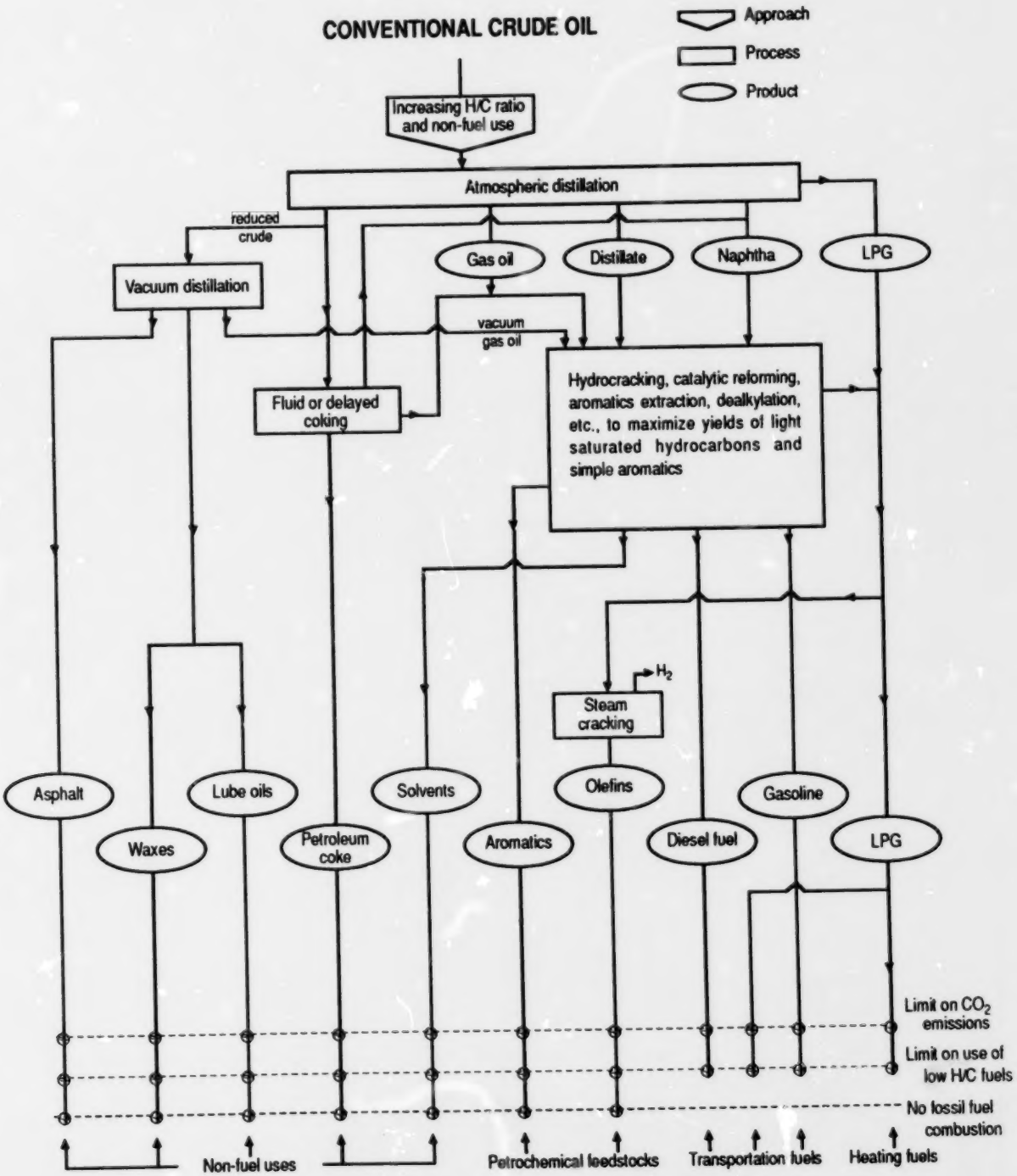


Figure 1-4. Options for Reducing CO_2 Emissions from Natural Gas Use

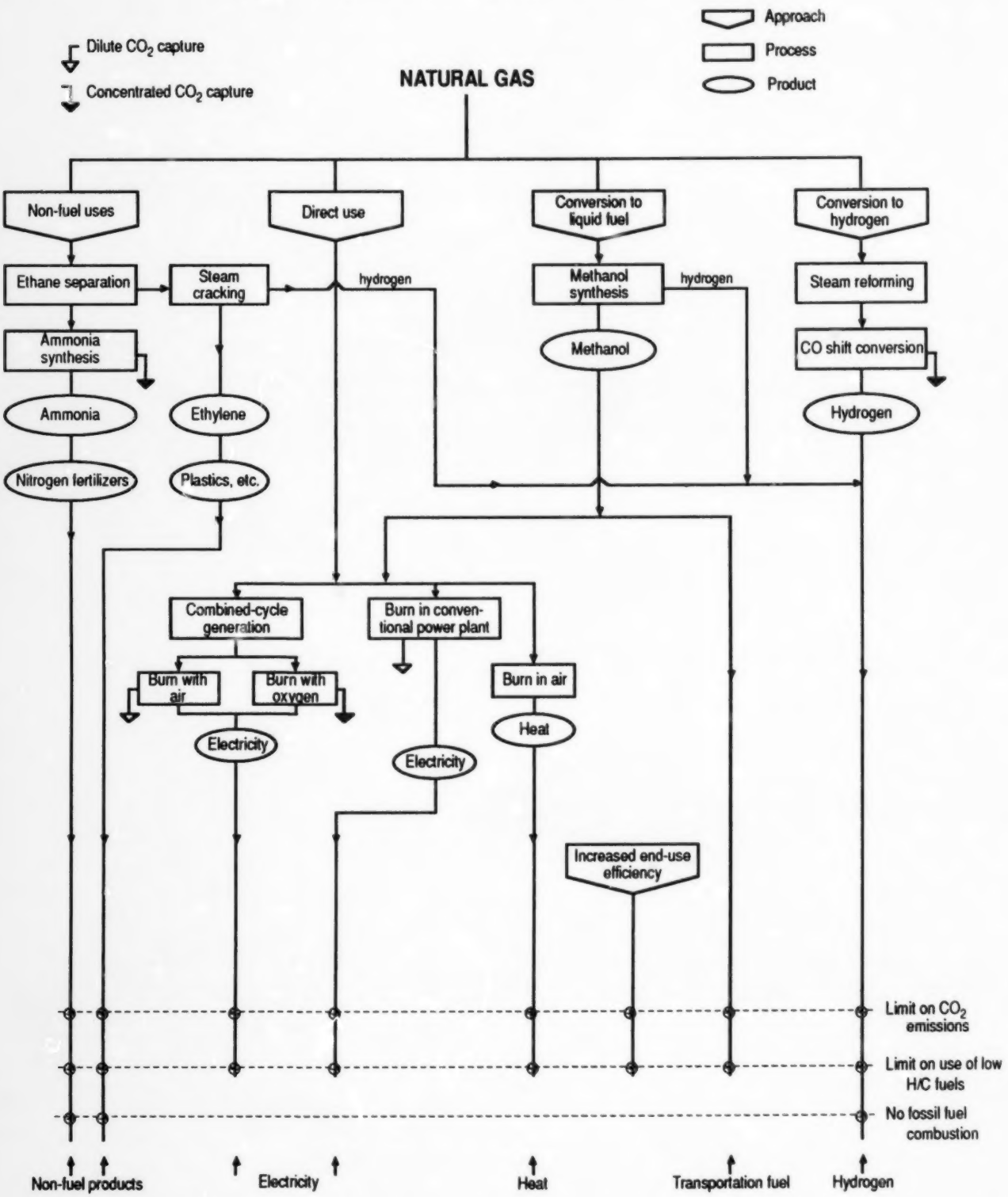


Figure 1-5. Options for Reducing CO_2 Emissions in Electric Power Generation

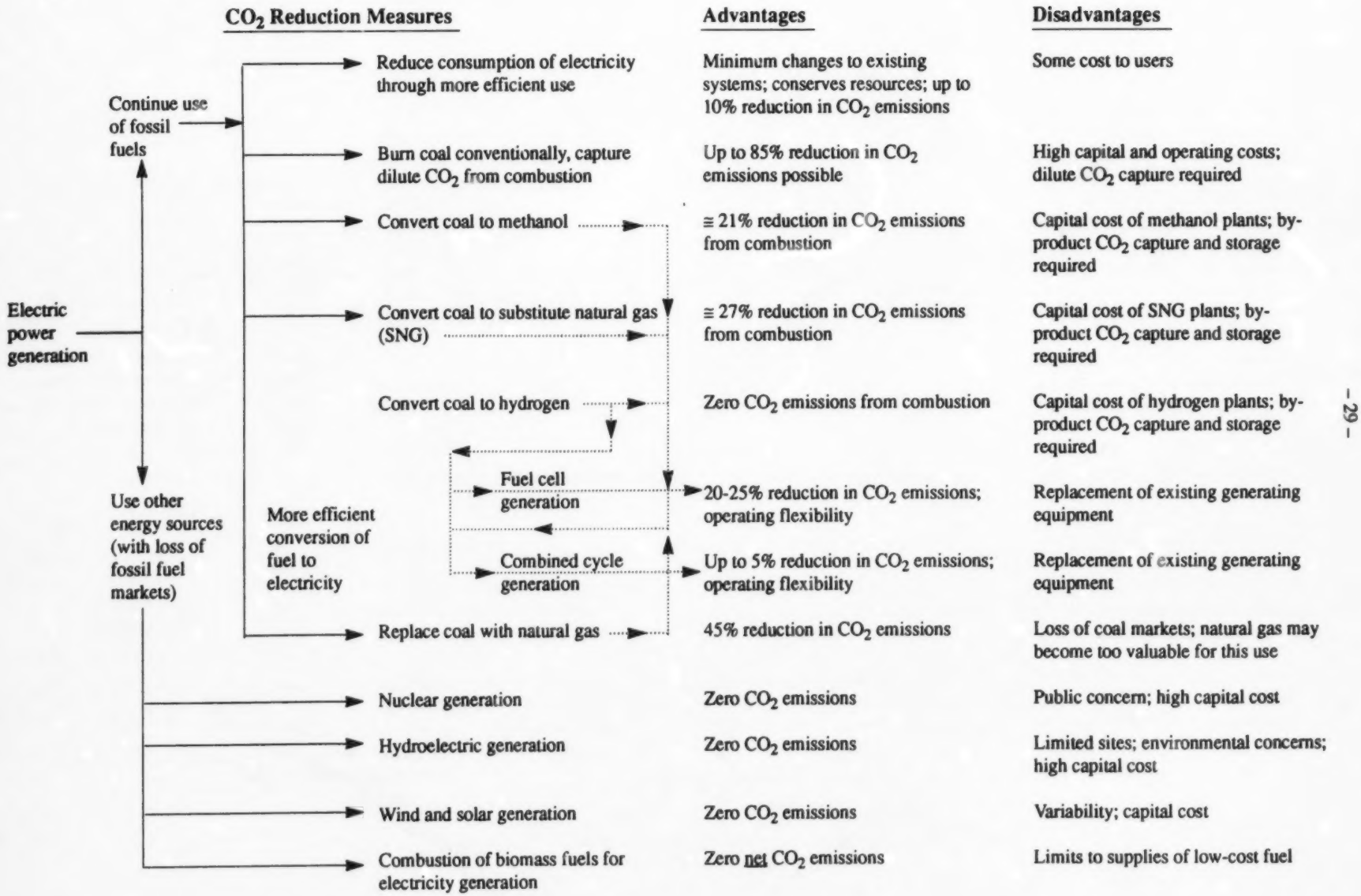
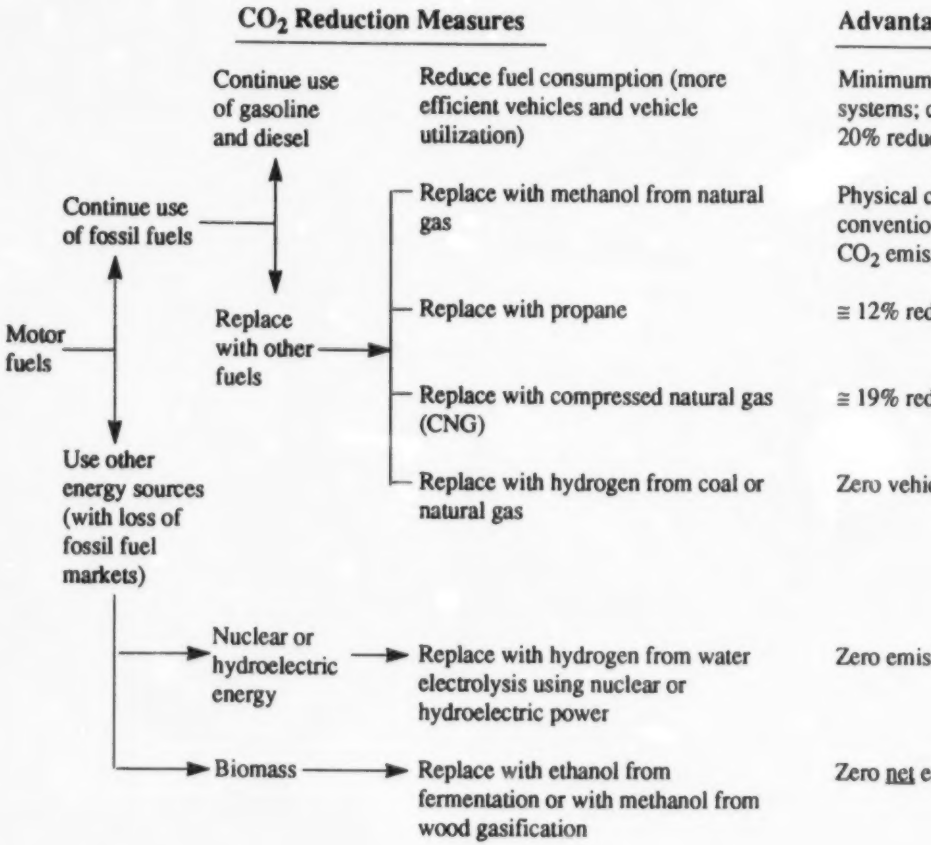
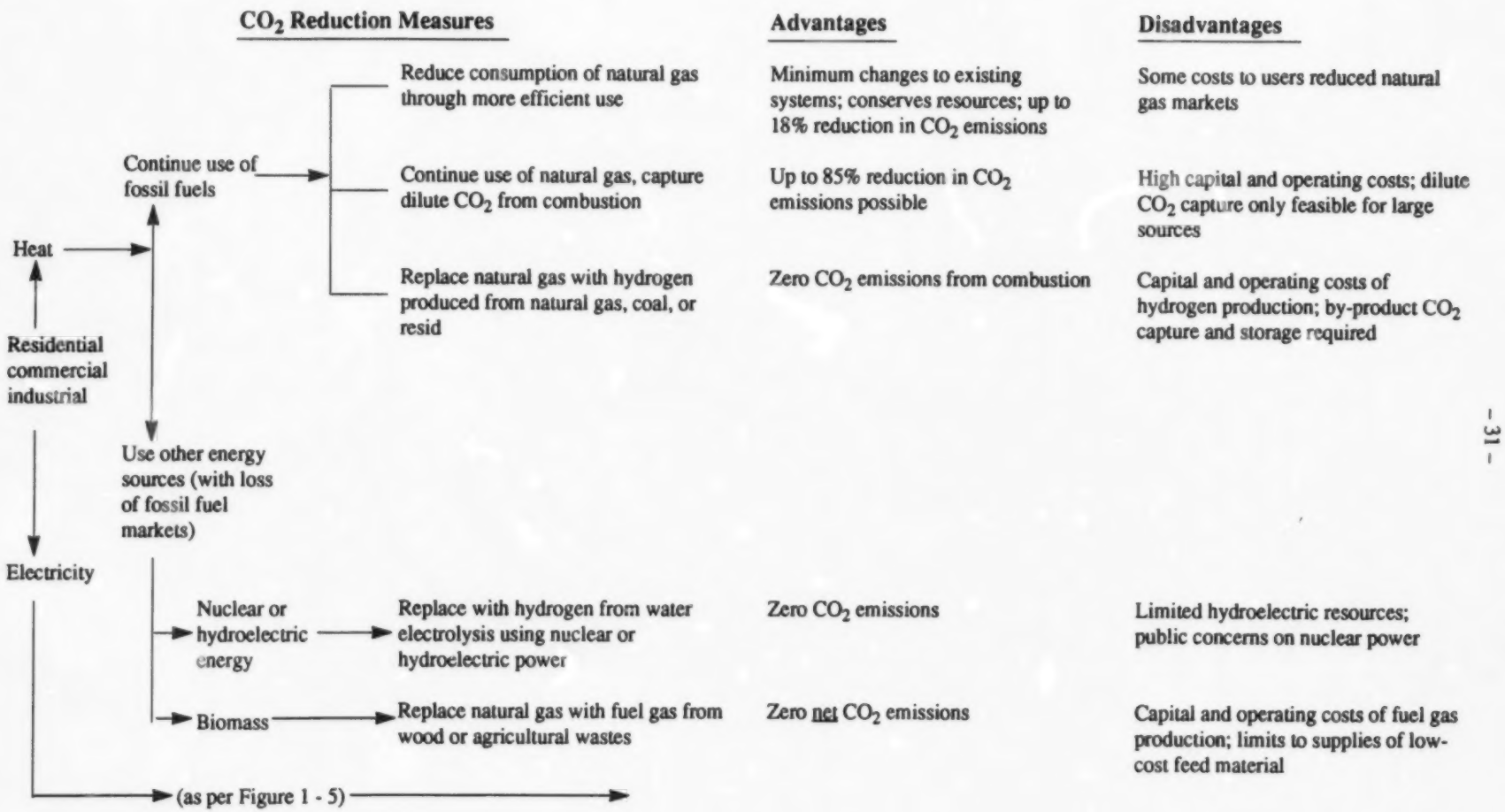

CO_2 Reduction Measures
Advantages
Disadvantages
Electric power generation
Continue use of fossil fuels
Use other energy sources (with loss of fossil fuel markets)
More efficient conversion of fuel to electricity
Reduce consumption of electricity through more efficient use
Minimum changes to existing systems; conserves resources; up to 10% reduction in CO_2 emissions
Some cost to users
Burn coal conventionally, capture dilute CO_2 from combustion
Up to 85% reduction in CO_2 emissions possible
High capital and operating costs; dilute CO_2 capture required
Convert coal to methanol
≡ 21% reduction in CO_2 emissions from combustion
Capital cost of methanol plants; by-product CO_2 capture and storage required
Convert coal to substitute natural gas (SNG)
≡ 27% reduction in CO_2 emissions from combustion
Capital cost of SNG plants; by-product CO_2 capture and storage required
Convert coal to hydrogen
Zero CO_2 emissions from combustion
Capital cost of hydrogen plants; by-product CO_2 capture and storage required
Fuel cell generation
20-25% reduction in CO_2 emissions; operating flexibility
Replacement of existing generating equipment
Combined cycle generation
Up to 5% reduction in CO_2 emissions; operating flexibility
Replacement of existing generating equipment
Replace coal with natural gas
45% reduction in CO_2 emissions
Loss of coal markets; natural gas may become too valuable for this use
Nuclear generation
Zero CO_2 emissions
Public concern; high capital cost
Hydroelectric generation
Zero CO_2 emissions
Limited sites; environmental concerns; high capital cost
Wind and solar generation
Zero CO_2 emissions
Variability; capital cost
Combustion of biomass fuels for electricity generation
Zero net CO_2 emissions
Limits to supplies of low-cost fuel

Figure 1-6. Options for Reducing CO_2 Emissions in the Transportation Sector


Motor fuels
Continue use of fossil fuels
Continue use of gasoline and diesel
Replace with other fuels
Use other energy sources (with loss of fossil fuel markets)
Nuclear or hydroelectric energy
Biomass

CO_2 Reduction Measures	Advantages	Disadvantages
Reduce fuel consumption (more efficient vehicles and vehicle utilization)	Minimum changes to existing systems; conserves resources; up to 20% reduction in CO_2 emissions	Some costs and loss of performance to vehicle users
Replace with methanol from natural gas	Physical characteristics similar to conventional fuels; ≅ 11% reduction in CO_2 emissions	Capital cost of methanol plants; some engine modifications needed to use 100% methanol
Replace with propane	≅ 12% reduction in CO_2 emissions	Limits to availability; some increase in fire risk
Replace with compressed natural gas (CNG)	≅ 19% reduction in CO_2 emissions	High pressure refuelling and vehicle fuel storage
Replace with hydrogen from coal or natural gas	Zero vehicle emissions of CO_2	Capital and operating costs of hydrogen plants; changes to fuel handling system and vehicle fuel storage; by-product CO_2 capture and storage required
Replace with hydrogen from water electrolysis using nuclear or hydroelectric power	Zero emissions of CO_2	Limited hydroelectric resources; public concerns on nuclear power; changes to fuel system
Replace with ethanol from fermentation or with methanol from wood gasification	Zero net emissions of CO_2	Capital and operating costs of fuel production; limits to supplies of low-cost feed material

Figure 1-7. Options for Reducing CO_2 Emissions in the Residential, Commercial and Industrial Sectors


CO_2 Reduction Measures
Advantages
Disadvantages
Reduce consumption of natural gas through more efficient use
Minimum changes to existing systems; conserves resources; up to 18% reduction in CO_2 emissions
Some costs to users reduced natural gas markets
Continue use of fossil fuels
Continue use of natural gas, capture dilute CO_2 from combustion
Up to 85% reduction in CO_2 emissions possible
High capital and operating costs; dilute CO_2 capture only feasible for large sources
Heat
Replace natural gas with hydrogen produced from natural gas, coal, or resid
Zero CO_2 emissions from combustion
Capital and operating costs of hydrogen production; by-product CO_2 capture and storage required
Residential commercial industrial
Use other energy sources (with loss of fossil fuel markets)
Electricity
Nuclear or hydroelectric energy
Replace with hydrogen from water electrolysis using nuclear or hydroelectric power
Zero CO_2 emissions
Limited hydroelectric resources; public concerns on nuclear power
Biomass
Replace natural gas with fuel gas from wood or agricultural wastes
Zero net CO_2 emissions
Capital and operating costs of fuel gas production; limits to supplies of low-cost feed material
(as per Figure 1 - 5)

Appendix 2

Calculation of Effects of Measures to Reduce CO_2 Emissions

The three general measures considered in this appendix are increased H/C ratios, capture of CO_2, and increased energy utilization efficiency. These measures will probably be used in combination to meet the desired CO_2 reduction target at the lowest cost, and they also interact to some extent. The other measures discussed in the study such as the growth of vegetation to remove CO_2 from the atmosphere and the possible reductions in non-fuel emissions are essentially independent of the first three. Consequently they may be estimated separately and simply added to the reductions calculated below.

The effects of increased H/C ratios, CO_2 capture, and increased utilization efficiency may be expressed as variations from a "base case" which is taken as the quantity of CO_2 currently being released to the atmosphere in Alberta from the production, processing, and combustion of fossil fuels.

I Base Case

The base case emissions are the sum of the following:

- CO_2 produced by direct combustion of fuels in the various energy use sectors
- CO_2 produced by combustion of fuels for generation of electricity
- CO_2 from fuels burned for energy or flared during the production, processing, or pipelining of fuels
- CO_2 obtained as a by-product from processes such as hydrogen production for fuel upgrading
- CO_2 originally contained in raw natural gas and removed during processing.

In the following expressions:

F = energy equivalent of fuel burned in a particular form and energy use sector (TJ/yr)
C = CO_2 produced per unit of combustion energy from a particular fuel (t/TJ)
Q = CO_2 emissions (t/yr)
E = electrical energy consumed in a particular sector (TJ/yr)
f = fraction of electrical energy generated from a particular fuel
k = conversion efficiency from fuel to electricity
Q_P = CO_2 produced as a by-product of fuel processing (t/yr)
Q_N = CO_2 in raw natural gas processed in Alberta (t/yr)

The base case CO_2 emissions may be expressed in the general form:

$$Q_B = \sum F \cdot C + \sum E \sum \frac{f \cdot C}{k} + Q_P + Q_N \text{ t/yr} \qquad (1)$$

The following subscripts and superscripts are used in the expanded form of the base case:

Subscripts (energy use sector)

- r = residential
- c = commercial
- i = industrial (excluding fuel processing)
- t = transportation (road, rail, air)
- p = production, processing and pipelining of fuels
- e = electric power generation

Superscripts (type of fuel)

- n = natural gas
- p = propane
- g = gasoline
- d = diesel fuel
- t = turbo fuel
- c = coal
- x = heavy fuel oil
- y = oil sands coke
- z = process gas

} fuel processing sector

- a_1, a_2, etc. = any fuels

Examples: F_r^n = natural gas burned in the residential sector, TJ/yr

C^n = CO_2 produced by combustion of natural gas, t/TJ

Neglecting sources which contribute less than 1% of CO_2 emissions in each energy use sector, the base case becomes:

$$Q_B = \left(F_r^n + F_c^n + F_i^n + F_t^n\right) C^n + \left(F_r^p + F_c^p + F_i^p + F_t^p\right) C^p$$

$$+ \left(F_c^g + F_t^g\right) C^g + \left(F_c^d + F_t^d\right) C^d + F_r^c C^c \qquad \text{fuel combustion}$$

$$+ \left(E_r + E_c + E_i + E_p\right) \left(\frac{f^n C^n}{k^n} + \frac{f^c C^c}{k^c}\right) \qquad \text{electricity generation}$$

$$+ F_p^n C^n + F_p^d C^d + F_p^x C^x + F_p^y C^y + F_p^z C^z \qquad \text{fuel production and processing}$$

$$+ Q_P + Q_N \qquad \text{by-product } CO_2 \text{ and } CO_2 \text{ in raw gas} \qquad (2)$$

The approximate values of F for 1988 are shown in the following table. In the case of electric power F = E/k, i.e., the fuel energy required to generate the electricity.

Table 2 - I

Base Case Fuel Consumption and CO_2 Emissions

F (PJ/yr)

fuel:	n	p	c	g	d	t	x	y	z	CO_2 10^6 t/y
Sector										
r	138	8	1							7.4
c	90	6								4.8
i	198	5			11					10.8
t		3		152	62	27				16.6
p	450		1		11		29	41	53	32.1
e	27		335							32.7
Totals	903	22	337	152	84	27	29	41	53	
C t/TJ	49.4	59.8	93.6	67.2	69.5	70	80.7	91	56	
Q 10^6 t/y	44.6	1.3	31.5	10.2	5.9	1.9	2.3	3.7	3.0	104.4

By-product CO_2 Q_P = 1.2

CO_2 in raw gas Q_N = 5.2

Base case CO_2 emissions Q_B = 110.8 x 10^6 t/y

II Effects of Measures to Reduce CO_2 Emissions

1. Increased H/C Ratios

a) Fuel Substitution

Substitution with a fuel of higher H/C ratio will decrease the quantity of CO_2 emitted per unit of combustion energy. Assuming equal combustion and heat utilization efficiencies for the two fuels, the reduction in combustion emissions will be given by:

$$\Delta Q = F_1\left(C^{a_1} - C^{a_2}\right)$$

where C^{a_1}, C^{a_2} = CO_2 per unit energy from combustion of the original and replacement fuels

and F_1 = energy production replaced by new fuel

In order to calculate the over-all effect of fuel substitution on CO_2 emissions, it is also necessary to take into account the CO_2 emitted during production, processing, and transportation to the point of use.

if p^{a_1}, p^{a_2} = CO_2 per unit energy from production, processing, and transportation of the original and replacement fuels

$$\Delta Q = f_1\left[\left(C^{a_1} + P^{a_1}\right) - \left(C^{a_2} + P^{a_2}\right)\right] \quad (3)$$

The percentage decrease in the base case CO_2 emissions will be:

$$\Delta Q_B = \frac{F_1\left[\left(C^{a_1} + P^{a_1}\right) - \left(C^{a_2} + P^{a_2}\right)\right]}{Q_B} \times 100$$

Numerical Examples:

The greatest opportunity for reducing CO_2 emissions by replacing a low H/C ratio fuel with a higher H/C ratio fuel is in the replacement of coal (C^c = 93.6 t/TJ) by natural gas (C^n = 49.4 t/TJ) in electric power generation. Only limited information was available to the writer on CO_2 emissions during production, processing, and transportation of specific fuels, but it may be assumed for purposes of illustration that P^c = 1.0 t/TJ and P^n = 7.5 t/TJ. If all the coal used for electric power generation (335 PJ/yr) were replaced by natural gas

$$Q = 335\left[(93.6 + 1.0) - (49.4 + 7.5)\right]$$
$$= 12.6 \times 10^6 \text{ t/yr } CO_2$$

Smaller but significant reductions in CO_2 emissions could also be obtained by replacing gasoline and diesel fuel with propane or compressed natural gas. Neglecting differences in CO_2 emissions during production, processing, and transportation of the fuels, the reductions in CO_2 emissions if gasoline and diesel fuel were completely replaced would be as follows:

Table 2 - 2

Reduction in CO_2 Emissions by Vehicle Fuel Substitution

Replacement Fuel	Reduction in CO_2 Emissions 10^6 t/yr		
	Gasoline (152 PJ/yr)	Diesel Fuel (62.5 PJ/yr)	Total
Propane	1.09	0.61	1.7
Natural Gas	2.71	1.25	4.0

b) Fuel Conversion

The preceding examples illustrate the decrease in total CO_2 emissions possible by replacing a low H/C ratio fuel with an already-available higher H/C ratio fuel. However, if the high H/C fuel is obtained by

conversion of a lower H/C fuel, it will be necessary to take into account the CO_2 produced during the conversion process. This CO_2 may arise from fuels used to provide external heat to the process; as a by-product of the conversion reactions in carbon-rejection processes; or as a by-product of hydrogen production for hydrogen-addition processes.

The expression for the change in total CO_2 emissions through the use of higher H/C ratio fuels then becomes:

$$\Delta Q = F_1\left[\left(C^{a_1} - C^{a_2}\right) - \left(C_A + C_B\right)\right] \quad (4)$$

where C_A = CO_2 from combustion (and where significant, from the production, processing, and transportation) of external fuels, in t/TJ of fuel a_2 produced

C_B = by-product CO_2 in t/TJ of fuel a_2 produced

The over-all effect of converting a low H/C ratio fuel to a higher H/C ratio fuel will be to decrease the CO_2 emissions at the point of use but to increase the total CO_2 emissions, unless a non-fossil source of hydrogen is available. The real benefit is that the by-product CO_2 from fuel conversion is obtained in a concentrated and localized form which is much more readily captured than dilute CO_2 from a number of combustion sources.

Capture of By-Product CO_2 from Fuel Conversion:

The capture and disposal of by-product CO_2 from fuel conversion will require the expenditure of energy, which will itself lead to the production of additional CO_2 unless obtained from a non-fossil energy source. Assuming that the by-product CO_2 is recovered from the reaction products in a concentrated and relatively pure form by an amine or similar process, the only major energy requirement will be for compression. If purchased electric power is used, there will be no opportunity to capture the additional CO_2 except as part of a program to reduce power plant emissions. Even if the additional CO_2 is emitted on-site from engine-driven compressors, its capture may not be worth the effort as long as it represents only a small fraction of the by-product CO_2 since it will be in a dilute for.

A similar situation exists with respect to the dilute CO_2 produced when external heat is required for a fuel conversion process, as in steam-methane reforming (F_1 C_A in Equation 4). As noted in the text, it may be advantageous to use processes such as partial oxidation which generate the required heat for endothermic reactions internally and yield only concentrated CO_2. However, with such processes it may be necessary to take into account the CO_2 emissions associated with the production, processing and transportation of additional feedstock, when these are significant.

If there is no capture of CO_2 from external energy sources and r = the ratio of the CO_2 from production of energy for CO_2 capture to the quantity of by-product CO_2 captured, the net CO_2 capture is C_B (1 - r) and the CO_2 emission will be:

$$C_B - C_B(1 - r) = C_B r$$

and Equation (4) becomes:

$$\Delta Q = F_1\left(C^{a_1} - C^{a_2} - C_B r - C_A\right) \tag{5}$$

Numerical Examples:

In the following table:

C^{a_1} = CO_2 produced per unit of combustion energy from original fuel

C^{a_2} = CO_2 produced per unit of combustion energy from converted fuel

C_A = CO_2 emissions from auxiliary fuel used in conversion process

C_B = by-product CO_2 emissions

$C_T = C^{a_2} + C_A + C_B$

Table 2 - 3

CO_2 Production from Fuel Combustion and Conversion

	CO_2 t/TJ				
Conversion	C^{a_1}	C^{a_2}	C_A	C_B	C_T
Coal to substitute natural gas	93.5	49.5	6.5	109	165
Coal to methanol	93.5	60.5	5	80	145.5
Natural gas to methanol	49.5	60.5	0	0	60.5
Coal to hydrogen	93.5	0	7	118	125
Natural gas to hydrogen	49.5	0	12	38.5	50.5

(The values shown for C_A and C_B are illustrative only, since they will vary with the process used and the type of coal; the values of C^a have been rounded to the nearest 0.5 t/TJ.)

From equation (5), the reductions in CO_2 emissions from replacement by a converted fuel will be as follows, assuming that all of the by-product CO_2 but none of the CO_2 from auxiliary fuel are captured, that $r = 0.06$ with natural gas feedstock (gas engine compressors) and that $r = 0.1$ with coal feedstock (purchased electric power).

Table 2 - 4

Reduction in CO_2 Emissions by Fuel Conversion

	Decrease in CO_2 Emissions	
	t/TJ	10^6 t/yr *
Coal by SNG from coal	26.6	8.9
Coal by methanol from coal	20.0	6.7
Motor fuel by methanol from natural gas	7.4	1.6
Coal by hydrogen from coal	74.7	25.0
Natural gas by hydrogen from natural gas	35.2	16.2
Natural gas by hydrogen from coal	30.7	14.1
Motor fuel by hydrogen from natural gas	53.6	11.5
Motor fuel by hydrogen from coal	49.1	10.5

* assumes that all of the coal and motor fuel consumed in Alberta are replaced by the converted fuels, and that all of the natural gas except that used in fuel processing is replaced by hydrogen.

The replacement of coal by substitute natural gas produced from coal provides the same reduction in combustion emissions as natural gas itself, but also represents a striking example of the by-product CO_2 penalty. The reduction in combustion emissions will be 44 t/TJ, but the by-product CO_2 and the auxiliary fuel will add 115.5 t/TJ for an increase in total CO_2 production of 71.5 t/TJ, or 76% more than if the coal had been burned directly. The net CO_2 emissions after capture of by-product CO_2 will be 44 - 0.1 x 109 - 6.5 = 26.6 t/TJ less that from direct combustion of coal. The replacement of all the coal burned for electric power generation by SNG would reduce CO_2 emissions by 8.9 x 10^6 t/yr, or 9% of the base case emissions. The replacement of coal by methanol produced from coal would reduce CO_2 emissions by 20.0 t/TJ or 6.7 x 10^6 t/yr.

The replacement of gasoline and diesel fuel in all vehicular applications by methanol produced from natural gas would reduce CO_2 emissions by 1.6 x 10^6 t/yr. Methanol from coal would be unattractive in this application since the by-product CO_2 would be an order of magnitude greater than the reduction in vehicle emissions; however, the conversion of natural gas to methanol yields essentially no CO_2 if the by-product hydrogen is used as process fuel. This is a less efficient way of using natural gas than direct use as vehicle fuel in the form of CNG, but may be justified by the greater convenience of liquid fuels.

Carrying the concept of increased H/C ratio to its limit, the conversion of coal or natural gas to hydrogen will completely eliminate CO_2 emissions at the point of combustion, all of the carbon in the original fuel

being eliminated as by-product CO_2. Table 4 - 3 shows that the total CO_2 from conversion and combustion is significantly less when coal is converted to hydrogen (1255 t/TJ) that when it is converted to SNG (165 t/TJ) or to methanol (145.5 t/TJ). The replacement of coal by hydrogen produced from coal would yield a net reduction of 25 x 10^6 t/yr in CO_2 emissions, or 25% of the base case emissions. The replacement of motor fuels and natural gas by hydrogen produced either from coal or natural gas would also yield larger reductions in CO_2 emissions that any of the other fuel substitutions.

If a large reduction in total CO_2 emissions becomes necessary, it may prove more economical to move directly to hydrogen as fuel rather than go through the intermediate stage of SNG or methanol production with CO_2 capture from combustion gases. While hydrogen has some disadvantages relative to SNG and methanol such as lower energy density and less-convenient storage, these problems will have to be solved in any case if other parts of the world shift to a nuclear- or hydroelectric-based hydrogen economy.

2. Capture of CO_2 from Combustion

The technology currently available for recovering CO_2 from combustion gases such as power plant flue gas involves cooling and cleaning the gas, contacting the dilute CO_2 with an absorbing solution, regenerating the absorbing solution by heating to drive off concentrated CO_2, cooling the absorbing solution for recirculation, re-heating the exhaust gas for buoyant lift, and drying and compressing the recovered CO_2.

The limit to CO_2 removal from a gas stream by contact with an absorbing solution is reached when the partial pressure of CO_2 in the gas stream equals the partial pressure of CO_2 above the absorbing solution. Consequently, high CO_2 recovery is favored by high CO_2 concentrations in the gas stream, high gas pressures, and low CO_2 loadings in the absorbing solution. These factors facilitate high recovery of by-product CO_2 form a fuel conversion process, but work against the capture of CO_2 from combustion gases where the CO_2 concentration is typically 8% to 14% and the pressure essentially atmospheric.

Capture of 90% of the CO_2 from a flue gas initially containing 10% CO_2 requires reduction of the CO_2 partial pressure to 1 kPa which seriously limits the maximum CO_2 loadings with the usual solvent systems. This in turn requires high solvent recirculation rates and high energy consumption for regeneration. The ratio r of the CO_2 produced by the consumption of energy for CO_2 capture from combustion gases to the quantity of CO_2 captured will therefore be considerably higher than for by-product CO_2 capture from fuel conversion processes. Since the CO_2 from the provision of capture energy and the CO_2 to be captured will be at approximately the same concentrations and pressures, it will be advantageous to combine them before treatment. (This will happen automatically if the capture energy is obtained from the source which produced the main flue gas stream, as in a power plant.)

If the additional quantity of CO_2 produced from the energy required to capture a fraction K of the CO_2 emissions Q plus this additional quantity is taken as Q_t t/yr (Q_t will be greater than Q.r), then:

CO_2 captured = $(Q + Q_t)\,K$ t/yr

CO_2 emitted = $(Q + Q_t)(1 - K)$ t/yr

since $Q_t = (Q + Q_t)\,K \,.\, r$ $\qquad Q_t = Q\,\dfrac{K \,.\, r}{1 - K \,.\, r}$

and CO_2 emitted = $Q\left(1 + \dfrac{K \,.\, r}{1 - K \,.\, r}\right)(1 - K) = Q\,\dfrac{1 - K}{1 - K \,.\, r}$

net reduction in CO_2 emissions = $Q - Q\,\dfrac{1 - K}{1 - K \,.\, r}$

$$\Delta Q = Q\left[1 - \frac{1 - K}{1 - K \,.\, r}\right] \text{ t/yr} \qquad (6)$$

Numerical Example:

The information available to the writer on the performance of systems for CO_2 capture from combustion gases was insufficient to make more than a very rough estimate of the reductions in CO_2 emissions that might be obtained. A solvent system specifically designed for CO_2 recovery from flue gas is reported to be capable of recovering up to 98% of the CO_2, and a pilot plant using this solvent system and other process improvements has been operated at 90% recovery with r = 0.33 for heat and electric power requirements, exclusive of CO_2 compression.

Much of this energy is required in the form of low pressure steam for regenerating the absorbing solution, which might be obtained as by-product heat or by cogeneration of heat and electricity, depending on the type of operation which gives rise to the flue gas. Consequently the amount of additional fuel energy required should usually be less than 0.33, and a value for r of 0.3 to 0.35 might be sufficient to cover both regeneration and compression energy.

Using the possibly-optimistic assumptions that K = 0.9 and r = 0.3 the net reduction in CO_2 emissions would be:

$$\Delta Q = Q\left[1 - \frac{1 - 0.9}{1 - 0.27}\right] = 0.863\,Q$$

If applied to all electric power generation form fossil fuels, the resulting reduction in CO_2 emissions would be $.863 \times 32.7 = 28.2 \times 10^6$ t/yr, or 28% of the base case emissions. However, it should be recognized that this

decrease would be obtained at the expense of a 35% to 40% increase in energy consumption and high capital and operating costs.

3. Increased Energy Utilization Efficiency

A reduction in fuel consumption for a given end use will decrease combustion emissions and will also decrease CO_2 emissions from the production, processing and transportation of the fuel. Increased energy efficiency in fuel production and processing will also be very effective in reducing CO_2 emissions because of the large quantity of fuels processed in Alberta for use elsewhere.

An increase in energy utilization efficiency may be expressed as a decrease in the value of F for the appropriate energy use sector and fuel type, or in the value of E in the case of electrical energy. The resulting reduction in CO_2 emissions will be:

$$\Delta Q = \Delta F(C + P) \tag{7}$$

$$\text{or } \Delta Q = \Delta E\,(C^e + P^e) \tag{8}$$

$$\text{where } C^e + P^e = \frac{F^n\left(C^n + P^n\right)}{k^n} + \frac{F^c\left(C^c + P^c\right)}{k^c}$$

An increase in conversion efficiency from fuel to electricity may be expressed as an increase in k. If the efficiency of a particular power plant is increased from k to s .k and the quantity of electrical energy generated per year is E_1 , the resulting reduction in CO_2 emissions is given by:

$$\Delta Q = E_1\left(C^e + P^e\right)\left(\frac{1}{k} - \frac{1}{s.k}\right) \tag{9}$$

Numerical Examples:

The 1988 discussion paper by the Energy Conservation Branch of Alberta Energy identifies a potential reduction of 11% in natural gas consumption in the residential sector. From Table 2 - 1, F = 138 PJ/yr so $\Delta F = 0.11 \times 138 = 15.2$ PJ/yr. The CO_2 emissions from combustion of natural gas $C^n = 49.4$ t/TJ and from production, processing and transportation $P^n \equiv 7.5$ t/TJ, so the reduction in CO_2 emissions $\Delta Q = 15.2\,(49.4 + 7.5) = 865 \times 10^3$ t/yr.

Implementation of all of the reductions indicated in the discussion paper would reduce total natural gas consumption by 78.4 PJ/yr, gasoline and diesel fuel consumption by 42.8 PJ/yr, and fuel for electricity generation by 35.6 PJ/yr. The resulting decrease in CO_2 emissions would be about 11×10^6 t/yr, or 10% of the

base case emissions.

Increasing the conversion efficiency from 32% to 40% (s = 1.25) in a coal-burning power plant generating 5000 GWh/yr (18 PJ/yr) of electrical energy would reduce CO_2 emissions by:

$$\Delta Q = \frac{18 \times 93.6}{0.32}\left[1 - \frac{1}{1.25}\right] = 1.05 \times 10^6 \text{ t/yr}$$

Production of all fuel-generated electricity in Alberta at 40% conversion efficiency would decrease CO_2 emissions by about 6.5×10^6 t/yr, or 6% of the base case emissions.

4. Multiple Use of CO_2 Reduction Measures

In practice, CO_2 reduction measures will seldom be applied to an entire energy use sector at one time as implied by the preceding numerical examples, but instead by a series of individual applications to industrial plants, communities, or vehicle fleets. In the following expressions:

ΔQ_{FS} = total reduction in CO_2 emissions from increased H/C radio by fuel substitution

ΔQ_{FC} = total reduction in CO_2 emissions from increased H/C ratio by fuel conversion and by-product CO_2 capture

ΔQ_{CC} = total reduction in CO_2 emissions by capture of CO_2 from combustion products

ΔQ_{EE} = total reduction in CO_2 emissions by increased energy utilization efficiently

ΔQ_{FE} = total reduction in CO_2 emissions by increased conversion efficiency from fuel to electricity

From Equation (3) the total reduction in CO_2 emissions by increased H/C ratios from fuel substitution in a series of applications with energy requirements F_1, F_2, - - would be:

$$\Delta Q_{FS} = F_1\left(C^{a_1} - C^{a_2}\right) + F_2\left(C^{a_3} - C^{a_4}\right) + \quad - \quad -$$

$$= \sum F\left(C^a - C^b\right) \tag{10}$$

Similarly, from Equation (5) the total reduction in CO_2 emissions by increased H/C ratio from fuel conversion with by-product CO_2 capture would be:

$$\Delta Q_{FC} = F_1\left(C^{a_1} - C^{a_2} - C_B^1 r - C_A^1\right) + F_2\left(C^{a_3} - C^{a_4} - C_B^2 r - C_A^2\right) + \quad - \quad -$$

$$= \sum F\left(C^a - C^b - C_B r - C_A\right) \tag{11}$$

From Equation (6) the total reduction in CO_2 emissions by capture of CO_2 from combustion will be:

$$\Delta Q_{CC} = Q_1\left[1 - \frac{1-K_1}{1-K_1 \cdot r_1}\right] + Q_2\left[1 - \frac{1-K_2}{1-K_2 \cdot r_2}\right] + \; - \; -$$

$$= \sum Q\left[1 - \frac{1-K}{1-K \cdot r}\right] \qquad = \sum F \cdot C\left[1 - \frac{1-K}{1-K \cdot r}\right] \tag{12}$$

From Equations (7) and (8) the total reduction in CO_2 emissions from increased energy utilization efficiency will be given by:

$$\Delta Q_{EE} = \Delta F_1 C_1 + \Delta F_2 C_2 + \; - \; - \qquad = \sum \Delta F \cdot C \tag{13}$$

or $$\Delta Q_{EE} = \Delta E_1 C_1^e + \Delta E_2 C_2^e + \; - \; - \qquad = \sum \Delta E \cdot C^e \tag{14}$$

From Equation (9) the total reduction in CO_2 emissions through increased conversion efficiency from fuel to electricity will be given by:

$$\Delta Q_{FE} = E_1 \frac{C_1}{k_1}\left[1 - \frac{1}{s_1}\right] + E_2 \frac{C_2}{k_2}\left[1 - \frac{1}{s_2}\right] + \; - \; -$$

$$= \sum E \cdot \frac{C}{k}\left[1 - \frac{1}{s}\right] \tag{15}$$

A combination of two or more of the above measures may often be used in practice, either because this is necessary to obtain the desired reduction in CO_2 emissions or because it provides the most cost-effective solution. The reductions in CO_2 emissions by the various measures will still be additive as long as they are applied to <u>different</u> energy uses, i.e. the total reduction ΔQ_{TD} will be given by:

$$\Delta Q_{TD} = \Delta Q_{FS} + \Delta Q_{FC} + \Delta Q_{CC} + \Delta Q_{EE} + \; - \; - \; - \tag{16}$$

However, if several measures are applied to the <u>same</u> energy use with CO_2 emissions = Q_1 , the fractional reduction in emissions q/Q_1 produced by each successive measure will apply to the reduced quantity $(1 - q_a/Q_1)$ left by the previous measure, and the total reduction ΔQ_{TS} will now be:

$$\Delta Q_{TS} = \sum Q_1\left[1 - \left(1 - \frac{q_a}{Q_1}\right)\left(1 - \frac{q_b}{Q_1}\right) \; - \; - \; \right] + Q_2 \; - \; - \tag{17}$$

A major CO_2 emission control program will probably involve elements of both situations, with a combination of reduction measures applied to some CO_2 sources and only one to others. The over-all reduction in CO_2 emissions, including the measures discussed in Sections 4 and 6 of the study, will be as follows:

$$\Delta Q_T = \Delta Q_{TD} + \Delta Q_{TS} + \Delta Q_{PG} + \Delta Q_{NF} \qquad (18)$$

where ΔQ_{PG} = net removal of CO_2 from atmosphere by plant growth and ΔQ_{NF} = reduction in non-fuel emissions.

Example of Combined Measures:

The following example uses only measures which are based on existing technology and which can be implemented incrementally since they involve no very large front-end expenditures or major changes in end-use equipment.

(1) Implement 75% of the reductions in fuel and electric energy consumption projected in the 1988 Conservation Branch discussion paper:

$$\Delta Q_{EE} = 0.75 \times 11 = 8.3 \times 10^6 \text{ t/yr}$$

(2) Replace 85% of the coal used for electric power generation, after reduction in electric energy consumption from (1) above, by natural gas:

$$\Delta Q_{FS} = 0.85 \times 302.1 \ (94.6 - 56.9) = 9.7 \times 10^6 \text{ t/yr}$$

(3) Substitute propane for 50% of gasoline, and CNG for 50% of diesel fuel used in vehicles (after 15% reduction from (1) above):

$$\Delta Q_{FS} = 0.5 \ [129.3 \ (67.2 - 59.8) + 52.7 \ (69.5 - 49.4 \ ]$$
$$= 1.0 \times 10^6 \text{ t/yr}$$

(4) Reduce consumption and flaring of natural gas in the fuel production and processing sector by 10%, after increase of 257 PJ/yr in natural gas requirements for measure (2) above:

$$\Delta Q_{EE} = 0.1 \ (450 + 257 \times .15) \ \ 56.9 = 2.8 \times 10^6 \text{ t/yr}$$

Then

$$\Delta Q_T = 8.3 + 9.7 + 1.0 + 2.8 = 21.8 \times 10^6 \text{ t/yr}$$

$$\Delta Q_B = 21.8/110.8 \times 100 = 19.7\% \text{ of base case emissions}$$